Oceanus

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Ocean Life

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COVER: Bright yellow stony corals (*Enallopsammia*) stand like bare trees, 1,500 meters (4,500 feet) deep on the basalt flank of Manning Seamount, an extinct undersea volcano that is part of the New England Seamounts chain off the east coast of the United States. Nearby a lower-growing, pale pink soft coral (*Candidella*) is covered with darker pink brittle stars feeding on the coral polyps. (Photo taken with the ROV *Hercules*, courtesy of the "Mountains in the Sea" scientific party, NOAA, and the Institute for Exploration.)

Dear Reader,

This issue, devoted to the WHOI Ocean Life Institute, concludes our series on research by the WHOI Ocean Institutes. Starting in June, you will see a redesigned *Oceanus*, featuring articles and images that reflect the breadth of research at the Institution. *Oceanus* is now published continually online at **oceanusmag.whoi.edu**. Reading *Oceanus* online is free and you may sign up to receive E-mail alerts when new articles are published.

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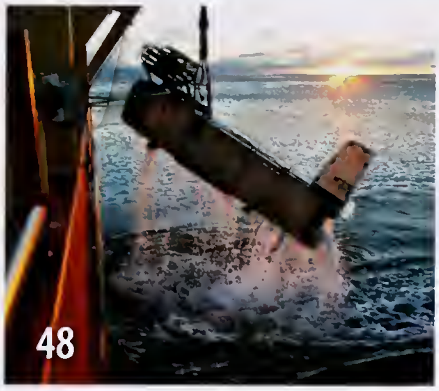

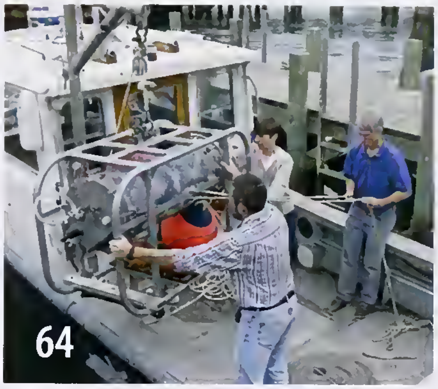

New Technologies

Woods Hole Oceanographic Institution
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The Ocean Life Institute

Discovering Life and Sustaining Habitats

The oceans cover 70 percent of the planet's surface and constitute 99 percent of its living space, and every drop of ocean water holds living things. Without its oceans, Earth would be a rock in space, and life may never have appeared on our planet.

The sea is the great experimental laboratory of evolution. In three billion years of Earth history, its waters have nurtured nearly every form of life that has ever existed, including probably the first entities that were truly alive. The ocean is home to the greatest part of Earth's biodiversity, containing 90 percent of the major groups of living things. They range from immense to minute and live everywhere, from geysers on the seafloor to the lips of lobsters.

In the 20^{th} century, new technology enhanced traditional collecting methods to locate organisms and characterize their habitats. Satellite pictures of light reflected from chlorophyll in the ocean revealed broad patterns of phytoplankton abundance, and satellite maps of ocean temperatures helped us understand the distribution of pelagic animals. Submersibles, manned and robotic, explored parts of the deep ocean never before visited, retrieving images and specimens of creatures new to human knowledge. Even surface waters yielded new discoveries of ubiquitous microbes, including photosynthetic bacteria responsible for half the primary production in the ocean. Revolutionary biotechnology concepts and methods, applied to life in the sea, helped us discover new organisms, untangle evolutionary relationships, explain adaptations, and reveal fundamental mechanisms of life.

Entering the 21^{st} century, ocean biology faces tremendous challenges—not only to understand the complex ecosystems of the sea, but to learn how to maintain the integrity, productivity, and resources of the ocean for the future. The sea and its biology is crucial for us and our planet—for balancing oxygen and carbon dioxide, for maintaining genetic diversity, and for producing food.

Human civilization is putting increasing pressure on ocean life, from overfishing, nutrient pollution, waste dumping, and climate change due to greenhouse effects. These are large and complex problems; understanding and alleviating them is essential.

But the promise is also great. We know the major problems and largely how they came about. We now understand better how fish populations respond to fishing pressure, how toxins affect marine animals, how nutrients stimulate phytoplankton blooms, how whales react to noise, or how species diversity maintains stable ecosystems.

Much of the information and technology for defining problems and identifying solutions is within our grasp, or will be soon. That knowledge and capability give us the basis for action to understand, sustain, and restore the ocean's ecosystems. Public awareness, funding, regulatory action, and economic adjustments are also needed, but with continued research, we can ensure that the necessary scientific knowledge will be at the ready.

The Ocean Life Institute (OLI) fosters research in ocean biology under three broad charges: Discover Life, Sustain Ecosystems, and Develop Tools. The goal for the OLI is to support pioneering basic science, both for its own value and to help solve important ecological and societal problems of the ocean.

Discover Life

This theme broadly includes exploration, discovery, and characterization of ocean organisms. The OLI has funded studies on new deep-sea microbes, fossil corals, and magnetic bacteria. Discovery may mean new information about where organisms live, how they evolved, and how their particular traits fit into the tapestry of marine communities. Often discovery happens when we look in familiar places with new tools and techniques.

Photo by Iain Kerr, Ocean Alliance

Sustain Ecosystems

Organisms together create communities that then provide stable habitats. These ecosystems, whether as small as a single coral head or as large as the Sargasso Sea, are maintained by the interaction of the particular organisms in the ecosystems with environmental forces, such as temperature, currents, nutrients, and sunlight. Changes in the abundance and diversity of key species (perhaps due to fishing or toxicity) or in the physical or chemical environment (from climate change or excess nutrients) can upset an ecosystem's equilibrium and lead to dramatic shifts that could decimate resources or imperil species survival. The OLI sponsors studies on toxicity of copper mine waste to seaweeds and industrial chemicals to fish, on responses of whales to stress, and on mathematical models to help manage fisheries and save threatened albatross populations.

Develop Tools

Even as it makes ocean life possible, water impedes research, and we need special equipment and techniques to extract specimens and information from the depths. New electronics, optics, computers, and molecular biology add a huge range of possibilities for tools to explore ocean life. Such tools, including biological and chemical sensors, can be deployed in many ways. Whether lowered from ships, borne on submarine vehicles, or mounted on moored or mobile observatories, these new sensors yield information on organisms both at small scales and over large distances and long time periods. New tools developed with OLI support include imaging systems for phytoplankton cells, heartbeat monitors for whales, and molecular probes to sample and identify microbes.

Jean Pigozzi

Laurence Madin, Ocean Life Institute director

Stewardship of the future rests on today's knowledge. Important decisions must be made soon about how to conserve, restore, or manage ocean environments and resources. Such efforts have often failed, lacking accurate information about biology and ecology.

The vision for the WHOI Ocean Institutes includes furnishing knowledge and awareness to those who need to use solid scientific information to benefit society and the environment. With this goal, the OLI has launched two research initiatives: First, to provide focused scientific information to help conserve the highly endangered North Atlantic right whale; and second, to provide life-history data needed for effective policies to regulate fishing on coral reefs and enable the rejuvenation of important reef species.

People breathe the ocean's oxygen, eat its fish, and marvel at the beauty of its inhabitants. But we also overreach in our harvest, pour our wastes into ocean waters, and damage the framework of many habitats. Achieving a new balance with the ocean will prove a challenge for the burgeoning human population, but one that can be met if we inform our actions with scientific knowledge.

—Laurence Madin

Laurence Madin, a transplanted fourth-generation Californian, makes his home in Massachusetts studying gelatinous animals such as medusae, siphonophores, ctenophores, and pelagic tunicates. Growing up in the San Francisco Bay area, he developed an appreciation for the natural world and the sea. He received an A.B. degree from the University of California, Berkeley, and a Ph.D. in zoology from UC Davis, having spent some of graduate school on a Bahamian island, helping pioneer the use of scuba diving to study plankton. Since coming to WHOI in 1974, he has also used submersibles and remotely operated vehicles to explore strange jelly creatures in deep water. Current projects include dynamics of salp blooms in the Atlantic and Antarctica; predation on larval fishes on Georges Bank; biogeography of plankton and fishes in the open ocean and deep sea; and developing new gizmos for sampling and exploration. Formerly chair of the Biology Department, Madin is the current director of the Ocean Life Institute, which has broadened his interests into tropical ecology, endangered whales, conservation biology, and policy. He still enjoys diving (even in Antarctica), photographing, and playing with plankton.

Coral Gardens in the Dark Depths

Scientists seek to learn more about these abundant, fragile, and now-threatened communities

**By Lauren S. Mullineaux, Senior Scientist
and Susan W. Mills, Research Associate
Biology Department
Woods Hole Oceanographic Institution**

The words "coral reefs" conjure up images of a tropical paradise: shallow, warm, aquamarine waters, bright sunlight, white sand, and colorful, darting fish. But corals also live deep in the sea, in regions where the sun doesn't penetrate and water temperatures remain just above freezing.

Until recently, deep-sea corals were relatively unknown. But as scientists have explored further and farther, they have found corals living in deep places throughout the world's oceans. Like their tropical cousins, deep-sea corals can be brightly colored and harbor a rich diversity of underwater life, including abundant commercially valuable fish.

Fishermen have discovered these deep-sea coral communities, too. Unfortunately, commercial trawling on seamounts has caused declines in the fish populations and serious damage to coral communities.

Like ancient, solitary, old-growth forests on land, these deep-sea coral communities may be easily disrupted and slow to recover. Once lost, they may disappear, along with the diverse, complex ecosystems they have sustained over long reaches of time.

Oases in a deep-sea desert

Scientists have learned that deep-sea corals tend to live in areas with rocky topography: on oceanic mountain ranges, the continental slope, and underwater volcanoes, or seamounts, whose slopes and canyon walls provide the two things corals need most: a hard surface to an-

Deep-sea coral photos courtesy of 'Mountains in the Sea' Scientific party, NOAA, and the Institute for Exploration

TOUCHED BY A COLD HAND—A colonial soft coral (octocoral) pulls in its small, whitish polyps upon contact by the manipulator hand of the remotely operated vehicle Hercules. *This coral (*Paragorgia*) is called "bubblegum coral" because of its color and bulbous branch ends. It is common on the New England Seamounts.*

chor to and access to food.

Corals cannot live on muddy or sandy bottoms. They must find something hard to attach to, such as rock or another coral skeleton. Topographic features in the deep sea create islands of habitat, surrounded by fine sediments that are inhospitable for corals.

Though corals may look like plants, they actually are colonies of animals, related to sea anemones. Each individual, or "polyp," is connected by tissue to others, and they live together, usually within a skeleton that they secrete for support.

Food and shelter

Deep corals differ from shallow-living, reef-building corals in several ways. They live in high and mid-latitudes, not just in the tropics. They need no sunlight, because they do not rely on the symbiotic relationship with photosynthetic algae, which provide food to shallow-living corals in exchange for a place to live. Instead, deep corals feed entirely on small plankton and organic particles—stirred up and brought to them by ocean currents that intensify when they hit undersea mountains.

These currents also feed a rich variety of other small animals that seek refuge from predators in the large, immobile corals, whose structures are as complex as the trunks and branches of a forest. Invertebrates such as brittle stars, sea stars, and feathery crinoids live directly on the coral colonies, and smaller animals burrow into the skeletons.

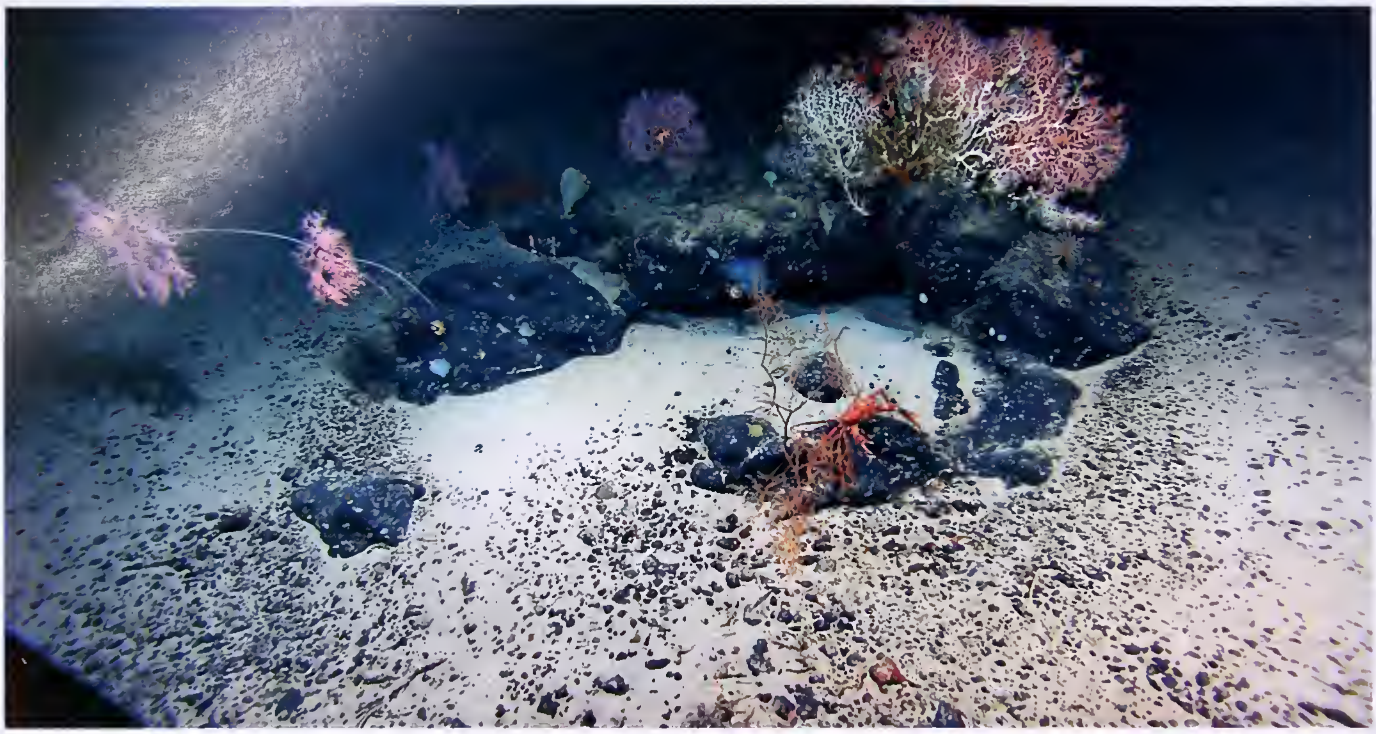
In the North Pacific, deep coral communities are inhabited by an abundance of fish, crabs, and other commercially important species. Dense schools of fish are associated with deep coral mounds off Norway and with a kind of coral called octocorals on seamounts off New Zealand.

All in all, the corals live in a quiet, stable neighborhood. In deep waters, temperatures and salinity levels are constant. In the depths, the communities are not exposed to hurricanes or buried by a falling rain of sediments, and natural disturbances are uncommon.

VENERABLE INVERTEBRATES—Deep-sea stony corals can attain great ages, and the hard skeletons of dead ones sometimes form mounds, tens of meters long and high, which support living colonies. This yellow stony coral has soft corals, feather stars, and brittle stars as neighbors.

HOT COLOR IN THE COLD DEPTHS—A pink bushy black coral, a white tree-like soft coral behind it, and a bright yellow sponge share a rocky seamount slope far below the reach of sunlight.

*CLEAN SLATES—Researchers placed blocks of basalt on a seamount's rocky surface to investigate whether larvae from other communities will settle near these two colonies of corals (*Paragorgia*). The blocks, next to a numbered marker and attached to yellow lines for retrieval, have been in place for a year.*



A HARD-ROCK FOUNDATION—Corals need a hard surface to grow on, like this circular outcrop of basalt. A red crab roams over sand and rock.

Stony, soft, or black

Though they may be found in the same habitats, three different types of corals live in the deep sea.

Stony coral skeletons are dense and rocky, often persisting long after coral colonies have died. The stony corals are related to shallow tropical reef-building species (*scleractinians*). They can form extensive mounds, reaching 12 kilometers in length and protruding as far as 30 meters above the seafloor.

Soft corals (or octocorals) often look like colorful undersea gardens of pink, red, and white. They grow in many different forms, including branching sea fans and sea pens. From a distance they look like bushes or trees, sometimes reaching two meters tall. An octocoral's flexible skeleton is formed by small spines (spicules) embedded in a firm organic substance.

NO VISIBLE MEANS OF SUPPORT—Black corals have many forms and colors. This unbranched "black whip coral," attached to the bottom, is supported only by the water.

The third type, black corals (*antipatharians*), are usually orange to tan, but secrete hard black proteinaceous skeletons. They have varied growth forms, including branching and unbranched shapes.

Scientists who have studied deep-sea coral species suggest that corals can live for hundreds of years. By measuring radioactive isotopes (with known half-lives) in their skeletons, scientists have calculated that some large colonies of the soft corals *Paragorgia* and *Primnoa* appear to be at least 500 years old. Reefs of stony corals *Lophelia* and *Oculina* are estimated to be more than 1,000 years old. Radiometric dating also indicates that the corals grow very slowly.

Two ways to reproduce

We still have very little information about how deep coral species reproduce, but we assume that it is similar to shallow species. Shallow-water corals reproduce sexually, or asexually, and some do both.

Asexual reproduction occurs through the production of buds that grow on the

colony, or by fragments that break off and settle near the parent colony. In fact, some researchers think that even very large mounds of stony coral (*Lophelia*) are formed by fragmentation, and that individual colonies are genetic clones of the first coral larvae that settled there.

Sexual reproduction produces microscopic larvae that disperse through the water—sometimes traveling far before they attach to a hard surface and grow. So far, scientists have rarely observed any sites with young deep-sea corals, indicating that these organisms do not disperse and colonize frequently or easily. Their slow growth rates, longevity, and infrequent colonization may make deep-sea coral communities more vulnerable to extinction when they are disturbed.

A CORAL LINE—A line of deep-sea corals recedes into darkness. From bottom left to top right: white, bushy soft corals, a bright orange black coral, a branched soft coral like a bare tree, and white, twisted, branchless bamboo corals. Sharing center stage in front are (from left to right) a dark, bottlebrush-shaped black coral, a red soft coral, and purple crinoids (relatives of sea stars).

Endangered communities?

Fishermen once avoided areas with deep-sea corals because they damaged their nets. Now, redesigned trawls and new techniques for removing corals enable fishermen to take advantage of these highly productive locales with less risk of losing gear. Recent damage to deep-sea coral ecosystems and declines in fish stocks have led conservation groups to call for fishing bans in areas with deep corals and the creation of marine protected areas in these places. (See "Do Marine Protected Areas Really Work?" page 42.")

To understand and predict how deep-sea coral communities will respond to and recover from disturbances, we need to know how often and where new colonies are established. Some communities might frequently receive incoming coral larvae from other coral colonies and therefore be resilient to disturbances. Others may be colonized rarely, making them less likely to recover from a disturbance and more vulnerable to extinction.

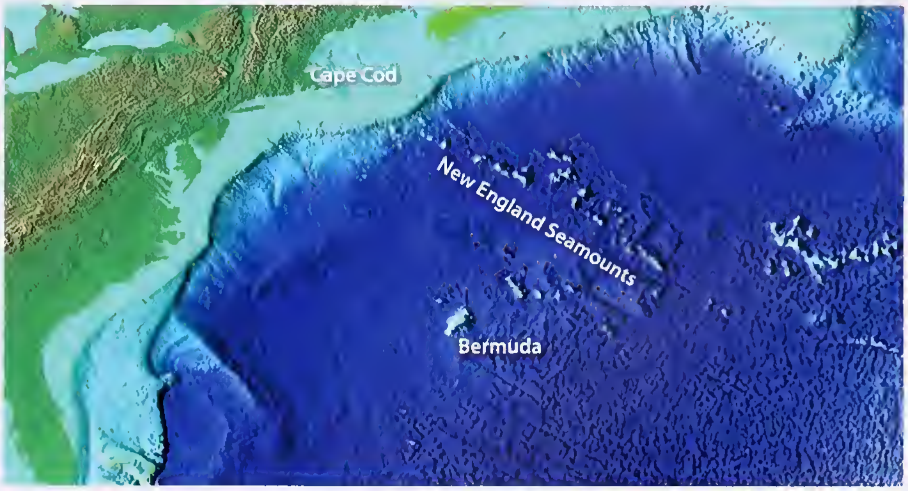
A second critical factor is where new colonists come from. If they arrive as larvae from remote populations, new settlers enhance the chances that a community will recover in the wake of a local catastrophe. But if new colonies form through fragmentation or budding from established colonies, then the source of new colonists expires when the parent colonies are destroyed.

Counting the newcomers

We use several methods to investigate how deep coral colonies recruit new settlers. First, we monitor and count coral communities for the appearance of new individuals. Second, we can measure settlement directly. On top of a seamount, we set out clean blocks of basalt, similar to the natural hard surface of the seamount. This provides new, uncolonized habitat for any corals to settle on. After a time, we recover the blocks and count the number of polyps that settled on them.

Some new corals appear to prefer to settle directly onto dead coral skeletons. To test this, we can also make experimental settlement surfaces out of biologically produced (biogenic) calcium carbonate that mimics coral skeletons.

In our first short-term colonization studies on Pacific seamounts, few larvae



FRAGILE OASES—Rising abruptly from the seafloor, seamounts are home to fragile ecosystems often dominated by corals. They are vulnerable to damage by fishing gear and are believed to be slow to recover. Many scientists recommend making them protected areas. The New England Seamount chain stretches from the New England coast toward the middle of the North Atlantic.

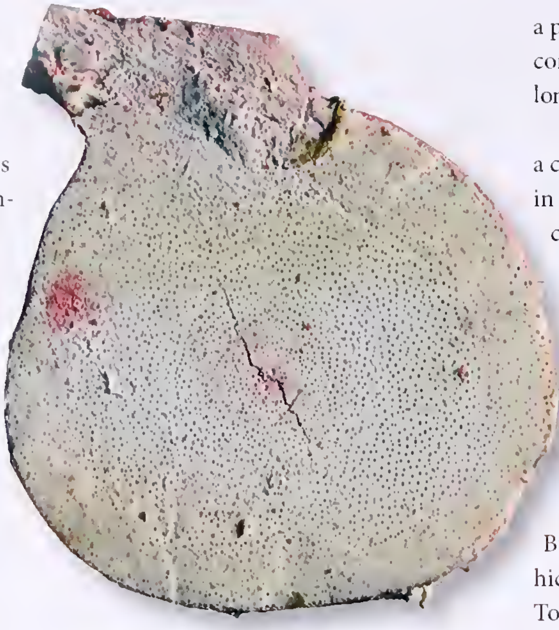
settled on our blocks. In a longer-term study on the New England Seamounts in the North Atlantic Ocean, we placed 20 blocks at two sites and recovered them after 10 months. No corals had settled in that time, though other invertebrates (anemones and snails) had. Because of the slow settling, we left the remaining blocks in place for an even longer time, and also placed blocks in different habitats at geographically separate sites.

Coral demographics

To gain insights into when colonies formed, we determine the ages of corals and map their locations within the communities. For instance, if we see a continuous range of ages in a community, including very young colonies, we can infer that colonization is still occurring, and at a fairly constant rate. If instead we see only very old individuals, we infer that a past colonization event established the community, but that new recruits are no longer arriving.

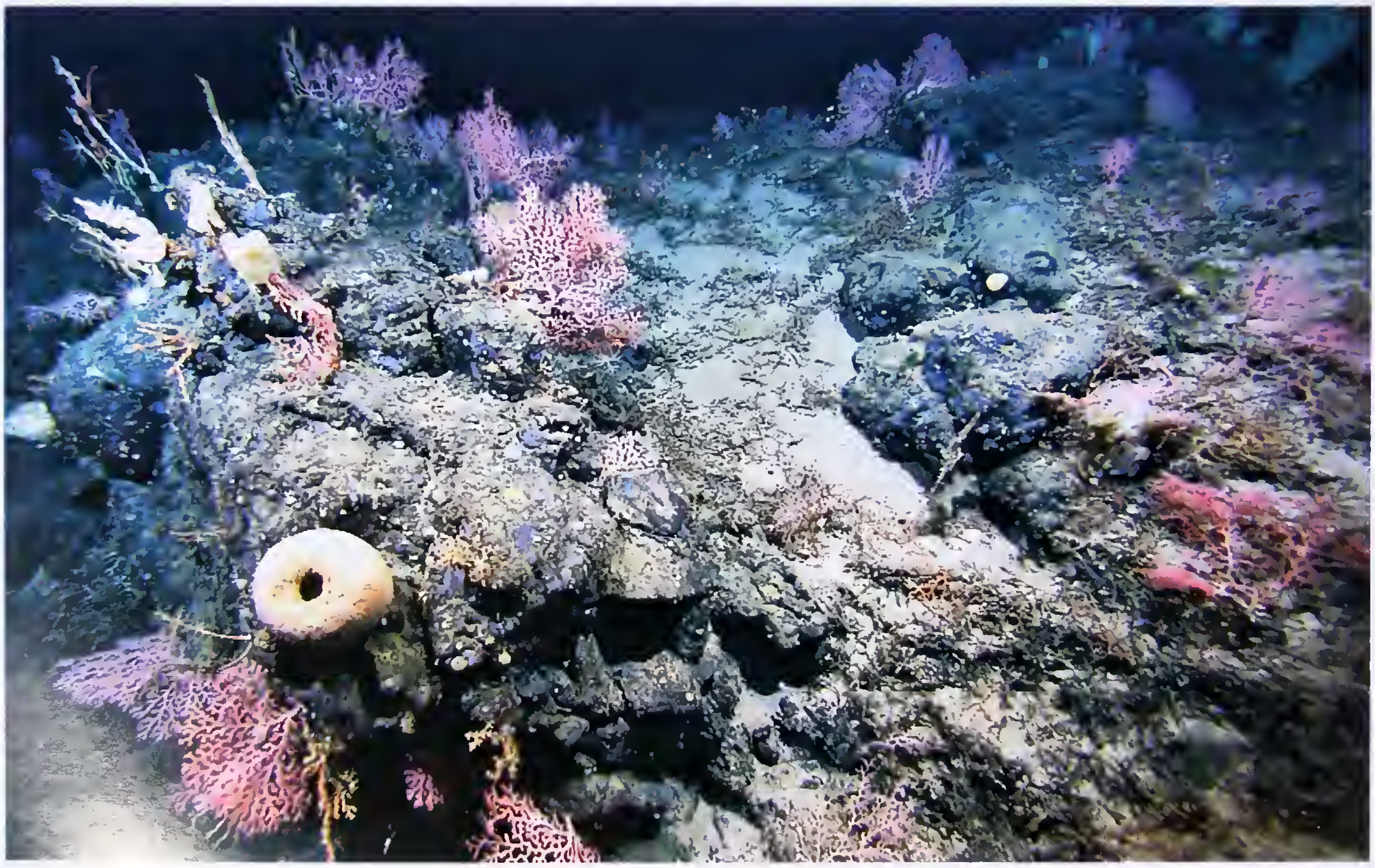
We also map the positions of corals in a community to determine the sequence in which the community was settled. If corals are reproducing by fragmentation, we expect the youngest colonies to be located near older colonies. But if colonists arrive as larvae from remote populations, we might not expect to see clusters of the same species.

For community-scale mapping, we examine images taken from cameras on the submersible *Alvin*. But to survey larger areas, we need vehicles with greater range and versatility. To search for new coral communities, a towed camera system is relatively inexpensive to operate and can be used from a ship during night hours when a human-occupied submersible is recharging batteries. Autonomous and remotely op-



Susan Mills, WHOI

CALCULATING CORAL AGES—By measuring the amount of a naturally occurring lead isotope (with a known half-life) in this section of a Paragorgia *trunk (actual size), scientists can determine how old the coral is.*



MIDNIGHT [illegible]—A deep coral community grows on volcanic rock in the New England Seamount chain. It includes an abundance of invertebrate animals, including pink, white, and orange soft corals, red-orange sea stars, and a multitude of light-colored sponges.

BLACK BUT ORANGE—Black corals can have several growth forms and external tissue colors. This one, bright orange and feathery, is nearly six feet tall. Their hard black internal skeletons are prized for jewelry.

erated underwater vehicles are also important tools, providing high-resolution topographic maps and seafloor images.

Genetic investigations

We are also using molecular genetic techniques to investigate where new corals come from, working with Scott France of the College of Charleston. By comparing the genetic composition of newly settled corals to those of established colonies, we can decipher whether more recent colonists come from a nearby or faraway source.

If the new colonies started from fragments or budding of locally established adults, they will be genetically identical to them. In contrast, corals from remote populations will have a different genetic makeup. If the new coral differs genetically from older colonies, and we know the genetic composition of other populations, then we may eventually be able to identify exactly where the new coral dispersed from.

Old-growth gardens

Because of deep-sea corals' impressive ages, slow and infrequent replacement, and role as habitat for diverse communities, they invite comparison with old-growth forests. However, they are quite different from terrestrial systems, and succession, change, and restoration in these communities may not follow any pattern we see on land. Only by carefully measuring the scale, speed, and sources of new recruits to deep coral communities will we be able to predict how and whether they can recover from the kinds of damage they now face.

Susan Mills, WHOI

Lauren Mullineaux is a biological oceanographer at Woods Hole Oceanographic Institution and faculty member of the MIT/WHOI Joint Program in Oceanography. She grew up in Colorado and started studying desert plant communities, but got hooked on oceanography after sailing on a research cruise in college. Currently, she studies the larval stages of marine invertebrates in order to understand how species disperse and colonize remote habitats. Much of her recent fieldwork has focused on the ecology of deep-sea communities, particularly on seamounts and at hydrothermal vents.

Lili Mills

Susan Mills came to Woods Hole in 1975, after finishing her bachelor's degree at Brown University. Working first at the Marine Biological Laboratory and then at WHOI, she has participated in projects including studies of population genetics of polychaete worms, identification of hydrothermal vent invertebrates in plankton samples, measurement of trace element concentrations in bivalve shells, and coral colonization at seamounts. Her work takes her to salt marshes in Massachusetts and deep-sea sites in the Atlantic and tropical Pacific—far too often, in the opinion of her husband. In her "spare time," she enjoys working on her lab's Web site, studying Spanish, and spending time with her family—especially traveling to South America with her two children to visit the countries where they were born.

Little Things Matter A Lot

Overlooked in the ocean until the 1970s, cyanobacteria are among Earth's most important organisms

EXTRAORDINARY ORGANISMS—The cyanobacterium, Trichodesmium thiebautii, *forms filaments (below) that contain many individual disk-shaped cells, each about 15 micrometers (10^{-6} meters) wide. Hundreds of* T. thiebautii *filaments join to create a macroscopic colony about 2.0 millimeters (10^{-4} meters) in diameter (above).*

John Waterbury, WHOI

By John Waterbury, Associate Scientist
Biology Department
Woods Hole Oceanographic Institution

When people think of bacteria, they usually think of germs—disease-causing agents that threaten human health. In reality, bacteria make life on Earth possible.

One group—the cyanobacteria—has completely transformed Earth's environment through their long history. Three billion years ago, ancestors of cyanobacteria infused Earth's ancient atmosphere with the byproduct of their photosynthesis—oxygen—changing the chemistry of the planet and setting the stage for entirely new oxygen-breathing life forms to evolve. Without the cyanobacteria, the life we see around us, including humans, simply wouldn't be here.

Before 1970, cyanobacteria were known to occur widely in fresh water and terrestrial habitats, but they were thought to be relatively unimportant in the modern oceans. This perception changed dramatically in the late 1970s and 1980s with the discovery of photosynthetic picoplankton by scientists at Woods Hole Oceanographic Institution and the Massachusetts Institute of Technology.

Tiny members of this group of newly discovered cyanobacteria, *Synechococcus* and *Prochlorococcus*, turn out to be the most abundant organisms on the planet today. They are at the base of the ocean's food chain, making air, light, and water into food for other life. Today, exploiting new biotechnological techniques, we are exploring their genes and uncovering the secrets of these extraordinary organisms.

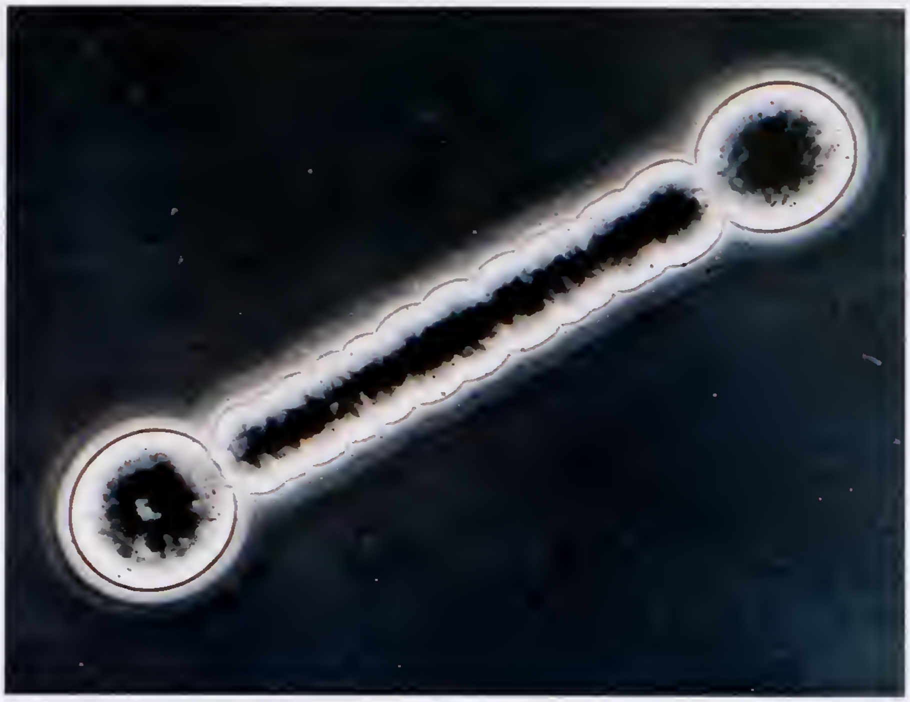
An unexpected glow

In 1977, I was on *Atlantis II* in the Arabian Sea with WHOI microbiologist Stanley Watson, measuring bacterial abundance and biomass. We were using a new technique employing epifluorescence microscopy: fluorescent dyes that labeled nucleic acids, making bacterial cells fluoresce green when excited with blue light.

But, to our great surprise, some samples contained cells that glowed a brilliant orange—before any dye was added. The color was produced by the natural fluorescence of phycoerythrin, the primary light-harvesting pigment in many cyanobacteria. This was our first introduction to *Synechococcus*.

To examine this new cyanobacterium, we attempted to culture it on that cruise, using media developed during my Ph.D. studies. But the cells died within 24 hours. It would take almost a year to develop media in which *Synechococcus* could successfully be isolated and grown in the laboratory.

We knew right away that *Synechococcus* was important by the impressive numbers of them that we found in seawater samples. Since 1977, they have been found everywhere in the world's oceans when the water temperature is warmer than 5°C (41°F) at concentrations from a few cells to more than 500,000 cells per milliliter (about 1/5 of a teaspoon), depending on the season and nutrients. This amazing abundance makes them a source of food for microscopic protozoans, the next organisms up in a food chain that ends in fish and mammals.


John Waterbury, WHOI

BARBELL BACTERIA—Cyanobacteria have mechanisms that allow two antagonistic physiological processes to coexist in the same organism: oxygen-producing photosynthesis and dinitrogen fixation, which is inhibited by oxygen. In Richelia *(above), the two processes are separated by space: Dinitrogen fixation occurs only in the bulbous, specialized cells (heterocysts) at the end of a 60-micrometer-long, filamentous cyanobacterium.*

Cycles of life

Bacteria take up the elements essential to life—especially carbon and nitrogen—and incorporate them into molecules that higher bacteria-consuming organisms use for growth. Bacteria also can reverse the transformation, returning elements to the environment, completing sequences of reactions known as nutrient cycles. Without the continuous cycling of these elements, all biochemical life processes would lead to a dead end.

Cyanobacteria are vital to two primary nutrient cycles in the ocean. In the carbon cycle, they photosynthetically "fix" carbon from air into organic matter at the base of the food chain, simultaneously releasing oxygen. Many are also important in the nitrogen cycle—a complex series of reactions and transformations, including one known as nitrogen fixation, which converts nitrogen from the air and incorporates it into cellular compounds. The key is cyanobacteria's ability to use molecular nitrogen (N_2, or dinitrogen) as a source of nitrogen for their cells.

Cyanobacteria live anywhere there is light and moisture: in the open oceans, in pristine or polluted lakes and streams, in soils, hot and cold deserts, hot springs, brine pools, and salt ponds. In symbiotic relationships with algae and plants, they provide nitrogen to their hosts in exchange for a site to live on.

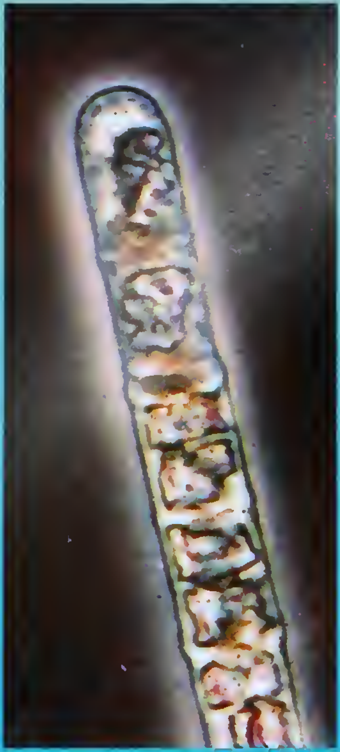
In many instances, cyanobacteria are visible to the naked eye. Their name is derived from one of their major light-harvesting pigments (phycocyanin), which has a characteristic blue-green color. In coastal oceans, cyanobacteria form dark blue-green mats covering rocks and mollusk shells in tidal pools. Along upper limestone shores, they form black crusts that erode rocks.

In salt marshes throughout the world, several types of cyanobacteria play a key ecological role in binding sediments by forming dense layered mats. In the tropics, these mats, called stromatolites, become thick; cyanobacteria inside them look almost indistinguishable from those in three-billion-year-old fossil stromatolites. This is evidence that cyanobacteria inhabited the seas when Earth was still young.

How oxygen got in the atmosphere

Three billion years ago, Earth's atmosphere contained little oxygen. But ancestral cyanobacteria thriving in the early oxygen-free oceans evolved a biochemi-

The "red" in the Red Sea



John Waterbury, WHOI

John Waterbury, WHOI

The cyanobacterium Trichodesmium erythraeum *forms filaments (left) made up of many cylindrical cells, each about 9 micrometers (10^{-6} meters) wide. Hundreds of filaments form a raft-shaped colony of* Trichodesmium erythraeum *several millimeters (10^{-4} meters) long (above). The raft is red because the cyanobacteria contain the red light-harvesting pigment, phycoerythrin. In calm weather, buoyant colonies rise to the surface in massive blooms that can cover thousands of square kilometers. These blooms gave the Red Sea its name.*

cal mechanism for photosynthesis, which used light to generate cellular energy by splitting water molecules, and producing oxygen in the process.

For a billion years, growing and multiplying in the sea, they slowly raised the oxygen level in the atmosphere to 20 percent, the level that supports oxygen-breathing life. Cyanobacteria alone, directly or indirectly, are responsible for all of the oxygen in our air.

In every case, the green plants we are most familiar with, from unicellular algae to trees, owe their photosynthetic abilities to small chlorophyll-containing bodies within their cells known as chloroplasts—which look a lot like cyanobacteria. In fact, most microbiologists believe that chloroplasts *are* derived from cyanobacteria—or, more precisely, that ancestral cyanobacteria entered larger cells and became symbiotic in them, giving them the ability to photosynthesize, and creating plants.

An ancient process

Both plants and cyanobacteria use carbon dioxide in air to synthesize cell carbon. But only bacteria can fix dinitrogen as a sole source of nitrogen in cells. Microbiologists believe this ancient process evolved very early, while Earth's atmosphere was still without oxygen, because the necessary enzyme, nitrogenase, is inactivated by oxygen.

Cyanobacteria have mechanisms that allow oxygen-producing photosynthesis and dinitrogen fixation—two antagonistic physiological processes—to coexist in the same organism. In some, the two processes are separated by time: Photosynthesis happens during daylight and dinitrogen fixation at night. In more complex species, the two processes are separated by space, with dinitrogen fixation occurring only in specialized cells (heterocysts) within filaments.

Trichodesmium, a filamentous cyanobacterium, plays an important ecological role by replenishing nitrogen in the central oceanic gyres—areas of widely circulating currents in the middle of oceans—where nutrients like nitrogen, required by other marine microorganisms for growth, would otherwise be low. In calm weather, their buoyant red-colored colonies rise to the surface, resulting in massive blooms that can cover thousands of square kilometers. These blooms gave the Red Sea its name.

Cultural breakthroughs

Trichodesmium quickly disintegrates when collected at sea and has been notoriously difficult to culture in the laboratory. In 1990, my lab at WHOI established conditions that made culturing routine and reliable by using very rigorous cleanliness. It turns out that instead of failing to add something these cyanobacteria required, we were inadvertently poisoning them with trace contaminants in our chemicals and on our glassware.

We can now grow four of the five species of *Trichodesmium* in the lab and use molecular genetic methods to study them. (See "The Deeps of Time in the Depths of the Ocean," page 17.) In collaboration with the U.S. Department of Energy's Joint Genome Institute, we have sequenced the entire genome of one *Trichodesmium* species. These advances give scientists at WHOI and elsewhere the ability to uncover the genetic reasons for *Trichodesmium*'s success.

We can also culture *Synechococcus*, and using molecular methods, scientists have found 12 distinct groupings, or clades, of marine *Synechococcus*, each approximately equal to a species. Scientists at the DOE's Joint Genome Institute have already sequenced the genome of one type, and others will soon follow.

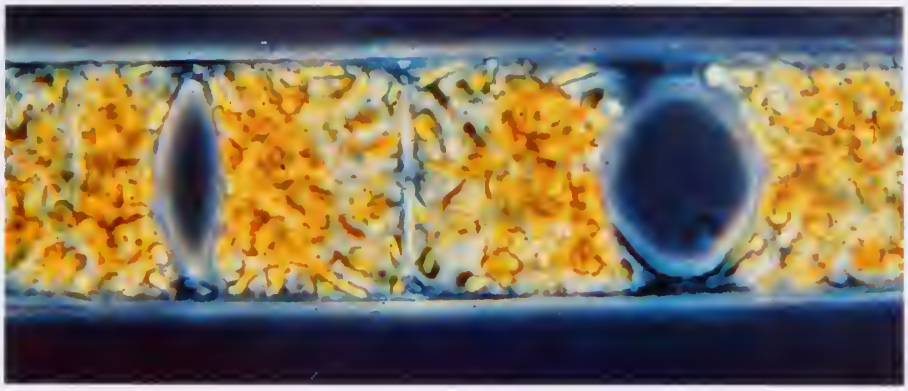
Scientists are examining the factors that control *Synechococcus*'s growth and distribution to understand more about their role in the ocean, especially in the food chain. Others are examining how *Synechococcus* coexists with a diverse and abundant group of cyanophages.

Microbial libraries

Even as we studied *Synechococcus*, new surprises awaited. In 1985 Robert Olson of WHOI and Sallie Chisholm of MIT discovered a second group of even smaller photosynthetic picoplankton in the Sargasso Sea, in the central North Atlantic Ocean. Olson took to sea, for the first time, an instrument that could count bacterial cells using fluorescence: the Flow Cytometer. The instrument led to the discovery of cyanobacteria ranging in size from 0.7 to 1.0 micrometers called *Prochlorococcus*.

It is our great fortune that these cyanobacteria can also be cultured in the lab. Scientists at MIT have assembled a collection of strains (cell lines) for *Prochlorococcus* collected from various places, while WHOI maintains collections for *Synechococcus*, *Trichodesmium*, and *Crocosphaera*, another recently discovered cyanobacterium. As a sort of lending library of cells, these two sites provide cultures for microbiologists all over the world to study.

Oceanographers measuring *Prochlo-*



Dave Caron, U. of Southern California

*THE INSIDE STORY—*Richelia *are cyanobacteria that live symbiotically inside single-celled marine plants called diatoms. The cyanobacteria have specialized dinitrogen-fixing cells that provide nitrogen to their hosts. Above is a light micrograph of the diatom* Hemiaulus sp. *Below is an epifluorescence light micrograph of the same cells, showing the red chloroplasts of the diatom and the orange fluorescence of the barbell-shaped endosymbiotic* Richelia.

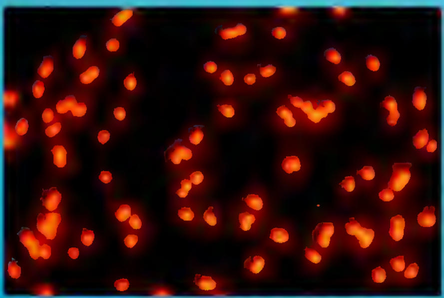
Dave Caron, U. of Southern California

Telltale fluorescence

Many biological compounds, including photosynthetic pigments such as chlorophylls and phycobiliproteins, fluoresce naturally when excited with light. This natural fluorescence played a key role in the discovery of marine photosynthetic picoplankton.

In 1977, we were using epifluorescence light microscopy to count bacteria in seawater, aided by fluorescent dyes that stained bacterial nucleic acids. *Synechococcus* was discovered when, quite by chance, we examined unstained samples and were immediately struck by the numerous small cells that fluoresced bright orange (below). The brilliant orange color results from the natural fluorescence of phycoerythrin, one of the phycobiliproteins abundant in cyanobacteria.

In 1985, WHOI scientist Rob Olson was the first to take a new instrument, the Flow Cytometer, to sea. It exploits fluorescence to study individual cells. With it, he and Sallie Chisholm of MIT detected very small cells with natural fluorescence of their chlorophylls. This unique "signature" led to the discovery of *Prochlorococcus*, which turn out to be among the most abundant organisms of Earth.



John Waterbury, WHOI

Tom Kleindinst, WHOI Graphic Services

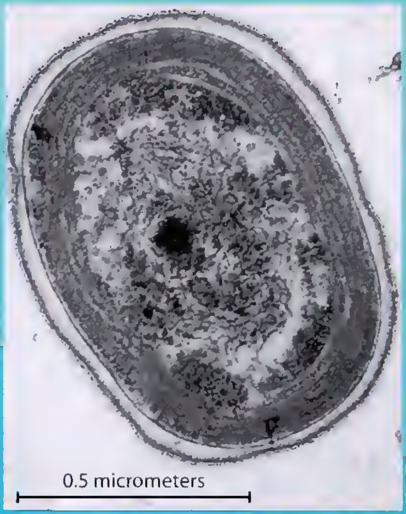
WHOI scientists Rob Olson and Heidi Sosik prepare to test a new-generation Flow Cytometer.

Eureka moments and cul-de-sacs

In 1975, Ralph Lewin from Scripps Institution of Oceanography found something scientists never knew existed—*Prochloron*, a symbiotic cyanobacterium living in sea squirts in Palau. It was a legitimate "Eureka moment," signifying the discovery of a previously unknown kind of organism known as prochlorophytes. But it also offered the tantalizing possibility of an even more momentous, heart-thumping discovery: how the first plant on Earth evolved.

Cyanobacteria inhabited the Earth billions of years ago, and scientists believe that ancestral cyanobacteria started symbiotic relationships with larger cells and provided them with the ability to photosynthesize. Eventually, these cyanobacteria evolved into chloroplasts, the photosynthetic factories inside all plant cells.

Prochlorophytes, like other cyanobacteria, contain chlorophyll a, a pigment important in photosynthesis. But unlike other cyanobacteria, which contain phycobiliproteins to absorb solar energy for photosynthesis, prochlorophytes contain chlorophyll b as their light-harvesting pigment.



Transmission electron micrograph of a thin section of Prochlorococcus sp.

So do all green plants.

Microbiologists speculated excitedly that prochlorophytes were on the same evolutionary pathway that led directly to chloroplasts in modern green plants.

But the theory didn't hold. Phylogenetic studies showed that the three known prochlorophytes (*Prochloron, Prochlorothrix*, and *Prochlorococcus*) evolved separately from within the cyanobacteria, and none was on the same line of descent leading to higher-plant chloroplasts. Although chloroplasts also arose from cyanobacteria, their modern cyanobacterial relatives have yet to be found.

The study of cyanobacteria demonstrates the strength of scientific inquiry. Scientists follow paths that lead sometimes to unexpected discoveries and sometimes to nowhere. But every line of investigation adds to our knowledge.

rococcus at sea have found staggering abundances in central oceanic gyres, where it can reach concentrations in excess of 100,000 cells in a milliliter of seawater. It may represent fully half the total photosynthetic production in these waters. Rough calculations, based on the surface area of the oceans and the abundance and distribution of *Synechococcus* and *Prochlorococcus*, suggest that these are the two most abundant organisms on Earth.

Cyanobacteria continue to surprise

Discoveries about cyanobacteria continue. We recently isolated *Crocosphaera*, a new genus of dinitrogen-fixing cyanobacteria, from the tropical Atlantic and Pacific Oceans. Surprisingly, these two-to-four-micrometer cells, which might otherwise occur in vast areas of the ocean, are relegated to the tropics by a quirk in their physiology: They cannot grow below 24°C (75°F).

Scientists have also found *Richelia*, cyanobacteria with specialized cells for fixing dinitrogen that live inside single-celled marine plants, including some diatoms. (See "Revealing the Ocean's Invisible Abundance," page 64.) With *Richelia* fixing dinitrogen for them, the diatoms form extensive blooms. Such symbiotic relationships between phytoplankton and dinitrogen-fixing cyanobacteria, once they can be successfully cultured, may be shown to play a significant role in the carbon and nitrogen cycles of the oceans.

Clearly, cyanobacteria, which have been so central to life on Earth, will continue to provide many new surprises, as scientists learn more about them.

John Waterbury grew up outside of New York City and spent summers sailing in Wellfleet, Mass. After graduating from the University of Vermont with a degree in zoology, he faced the option of a tour of duty in Vietnam or an offer to work with Stanley Watson at WHOI. The choice was both obvious and fortuitous. He spent four years working on nitrifying bacteria before Watson persuaded Roger Stanier at the University of California, Berkeley, to take him on as a graduate student. There he was drawn to cyanobacteria, a group that has remained the focus of his research ever since. Along the way, Stanier and his wife, a Parisian, moved to the Pasteur Institute in Paris. Waterbury tagged along, having finished his course work at Berkeley, to do his research in Paris. After three formative years there, with Ph.D. in hand, he headed back to Woods Hole, where he has been ever since.

The Deeps of Time in the Depths of the Ocean

Discoveries of unusual marine microbes are radically changing our views about the evolution of life

**By Andreas Teske, Associate Professor
University of North Carolina at Chapel Hill
and Katrina Edwards, Associate Scientist
Marine Chemistry & Geochemistry Dept.
Woods Hole Oceanographic Institution**

At the helm of the *Endeavor*, James Cook set sail from England in 1768. He rounded Cape Horn in January 1769, entering the vast, unexplored Pacific and Southern Oceans and opening up an entirely new vista on the world.

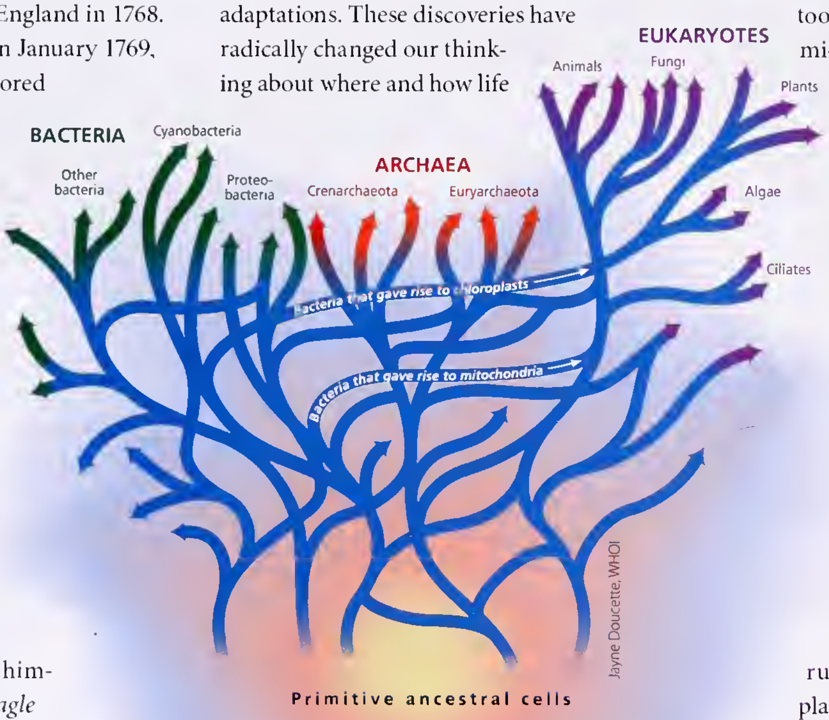
Cook "added a hemisphere" to the body of European knowledge, said the naturalist Charles Darwin. He discovered new Pacific islands and Australia. He found never-seen-before animal species and more than 1,000 exotic species of plants.

In the 1830s, Darwin himself sailed aboard the *Beagle* to the Galápagos Islands. The observations he made there of animal life spurred his theory of natural selection, which revolutionized our understanding of the origin and evolution of species.

Centuries after these classical voyages, we are making discoveries that are similarly shaking and expanding prevailing ideas about life on our planet. Once again we have embarked on voyages to explore remote, unknown areas of our planet—this time in, rather than on, the oceans.

Wherever we have looked in the oceans, we have found previously unknown microorganisms. We have often found them living in conditions once thought to be incompatible with life, using unfamiliar physiologic and metabolic adaptations. These discoveries have radically changed our thinking about where and how life may have originated and evolved on this planet, and where it might exist on others.

The seafloor and the rocky regions below it offer boundless new potential habitats to explore. With research submersibles, robotic vehicles, and new sampling tools and techniques, marine microbiologists are making discoveries at an unprecedented rate. We are opening a wide window onto the immense, unexplored realm of the smallest, least-known, but most important life forms. We have entered the classical age of microbiology.

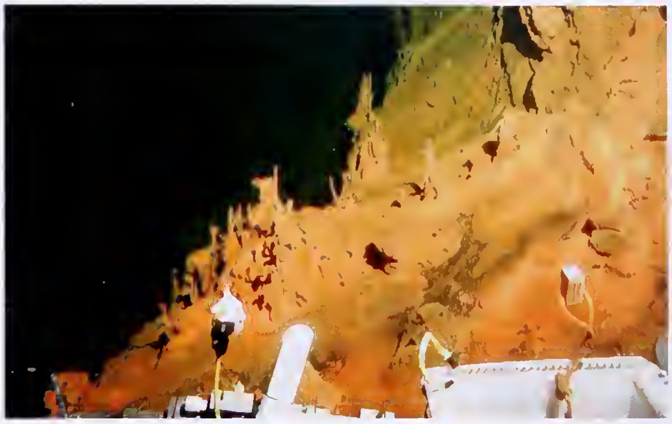


A COMPLEX TREE OF LIFE—Microbes are living archives of Earth's evolutionary history. The discovery of a great variety of deep-sea microorganisms (using diverse metabolic strategies to live in diverse habitats) indicates that they evolved along different evolutionary pathways. Using genetic analyses, scientists can trace these pathways to reconstruct when various microbial biochemical and metabolic machinery developed, diverged, or intermingled in the three major domains of life: bacteria, archaea, and eukaryotes.

Recent discoveries

Without microorganisms, there would be no other life on Earth. Unseen, ubiquitous, and unicellular, microorganisms nevertheless keep the planet running. Photosynthesizing plankton form the base of the marine food chain and keep the biosphere well oxygenated. At the other end of the cycle, other microbes decompose organic molecules for reuse.

It was not until 1977 that we discovered cyanobacteria in the open ocean, which turn out to be among the most abundant and important bacteria on Earth. These bacteria were the photosynthetic pioneers responsible three billion years ago for infusing our planet's atmosphere with oxygen. (See "Little Things Matter A Lot," page 12.)



Terry Kirby, University of Hawaii

MICROBES IN MANY COLORS—Scientists have found a multitude of deep-sea microorganisms using a variety of chemical compounds to live. Yellow bacterial mats atop sediments in the Guaymas Basin in the Sea of California (left) are evidence of microbes that oxidize sulfide; the sediments underneath harbor methane-oxidizing archaea. The orange mats at right are made by microbes that live off iron in seafloor rocks near Hawaii.

As recently as the mid-1970s, scientists believed there were only two domains of life on Earth: prokaryotes (single-celled bacteria, without nuclei or complex cellular structures) and eukaryotes (organisms made of cells with nuclei, ranging from single-celled amoebae to all multicellular life, including fungi, plants, reptiles, and mammals). Then in 1977, Carl Woese of the University of Illinois identified a wholly new domain of single-celled life forms, called archaea, which are as genetically different from bacteria as bacteria are from trees and people.

Archaea, or "ancient ones," have existed for billions of years on Earth. Many are extremophiles that thrive in hot, cold, salty, acidic, oxygen-depleted, or other extreme environments. Such conditions prevailed on an adolescent Earth, before cyanobacteria evolved and fundamentally changed Earth's atmosphere.

Life in unexpected places

In the late 1970s, we also discovered microbial communities in the dark and high-pressure depths of the seafloor—living on superheated, acidic, sulfide-rich fluids emanating from hydrothermal vents. Since then, we have found microbes that thrive in polar ice, on ocean floor lava, buried beneath seafloor sediments, and in the rocky nooks beneath the seafloor. They exploit a wide range of chemical reactions, using hydrogen sulfide, iron compounds, nitrites, methane, and other chemical compounds to obtain energy and resources to grow. (See "Revealing the Ocean's Invisible Abundance," page 64.)

This great variety of habitats and metabolic strategies indicates that microbes have taken a diversity of evolutionary pathways in the past. Ancient microbial lineages, which had their origin (and possible heyday) when different biogeochemical conditions prevailed on Earth, can survive today in diverse habitats that still exist in the mostly unknown deep subsurface of oceans. These microbes are living archives of Earth's evolutionary history.

The novel microbial lineages we are finding on Earth are also expanding and guiding our search for life that may exist in the extreme environments on other planetary bodies. With our eyes opened wider to more possibilities, we can look for life in previously unsuspected places: in the iron-rich rocks of the red planet, Mars; beneath the ice-covered surface of Jupiter's volcanic moon, Europa; or on Titan, Saturn's moon, which now shows evidence of having liquid-methane lakes to go along with its methane-rich atmosphere.

Portals into microspace

Like Cook and Darwin, today's scientists collect specimens in remote places, but studying microorganisms presents a new set of challenges. To study microbes, scientists need to keep them alive, but it is often hard to reproduce undersea conditions in the laboratory, and only some microbial species have been successfully cultured.

Instead, microbiologists have exploited modern genetic techniques to search for, identify, and study newly found microbes. They examine samples from deep-sea environments containing unknown species of microbes, locate gene sequences within them, and compare these sequences with those of known, cultured microbial species.

An unknown organism in the wild can be identified—on the basis of how similar gene sequences are to those of known microbes—without scientists ever having to grow it in the laboratory. Fully half of the bacterial branches known today have never been cultured and have been identified only by gene sequences.

Genomic investigations

Gene sequences also allow scientists to trace microorganisms' evolutionary history. All microorganisms share some common genetic equipment, including certain genes, known as "conserved genes," which are the blueprints for basic biochemical functions. Mutations that change gene sequences accumulate in genes over evolutionary time, but this process occurs at a far slower rate in conserved genes than in other genes. Thus, conserved genes are similar in closely

related organisms and less similar in distantly related ones. The greater the differences in conserved genes shared by two organisms, the further back in time they diverged in evolutionary history.

By analyzing the DNA of conserved genes, scientists can place microorganisms in evolutionary trees that encompass deep evolutionary time and chronicle when various microbial biochemical and metabolic machinery developed and diverged. Surveying samples from marine environments, microbiologists are finding novel gene sequences from unknown organisms and accumulating libraries of gene sequences to reference newer discoveries.

Little microbes that could

At the same time, microbiologists are also extracting nucleic acids from microbes to determine what protein products the nucleic acids code for. By these means, we can find out something about what compounds and biochemical mechanisms the microorganisms use to obtain energy and carbon to live and grow.

In addition, microbiologists are analyzing isotopes of elements incorporated into microbes during their metabolic processes. These not only provide more clues to learn about the microbes' biochemical machinery, they also reveal how the microbes affect the rocks they live in, seawater chemistry, and even the atmosphere.

In 2000, for example, we found new species of microbes that live directly off minerals in seafloor rock. They oxidize iron in the rocks to obtain energy and convert carbon dioxide in seawater into organic matter to grow.

If these previously unknown bacteria turn out to be as abundant as they seem to be, they may play a longstanding, important role in Earth's climate by extracting huge amounts of the greenhouse gas carbon dioxide from seawater and keeping it out of the atmosphere (while producing up to a million tons of biomass). They may have changed the geology of the seafloor by changing the chemical composition of seafloor rocks. They may have been evolutionary pioneers on an iron-rich, oxygen-poor early Earth, or inhabitants of iron-rich, oxygen-poor planets today, such as Mars.

No oxygen, no problem

Over the past few years we have sampled and analyzed sediments in the Guaymas Basin in the Gulf of California, where hundreds of meters of sediments have piled on top of hydrothermal vents. We had expected to find the molecular signs of archaea adapted to high heat (hyperthermophiles), which are well known at hydrothermal vents.

But instead we found something completely different—a major new type of archaea, related to known methane-producing archaea, or methanogens. We believe that the high geothermal heat emanating from the hydrothermal vent site is breaking down organic matter in the sediments into short-chain fatty acids, ammonia, and more methane.

Some of these compounds percolate upward and are released from the sediments into the ocean—but not all of them. In the sediments we also found isotopic and gene sequence signatures that reveal archaeal populations that use methane to grow in oxygen-free environments, such as those beneath the Guaymas sediments.

The discovery of these anaerobic methanotrophs fills a large gap in our knowledge of Earth's microbial and geochemical cycles. Microbes that generate methane, and others that consume it, play crucial roles in minimizing how much methane—a greenhouse gas more potent than carbon dioxide—is released from the ocean to the atmosphere.

These microorganisms complete a subsurface methane cycle that allows life to flourish at the seafloor, not only in the microbial oases of hydrothermal vent sites, but also in deep marine sediments and the subsurface biosphere. We are now exploring deep marine sediments in the Pacific to investigate whether this phenomenon is global.

Though the pace of microbial discoveries has increased, history warns us that we haven't seen everything yet. The book on microbial life, on Earth and elsewhere in the universe, is far from written.

Tom Kleindinst WHOI

Andreas Teske earned a master's degree in biochemistry in his native Germany. After deciding to seek work that allowed exotic field trips, he spent a year in the cornfields at the University of Illinois, focusing on microbial evolution and diversity, before joining the Max Planck Institute for Marine Microbiology for his Ph.D. on microorganisms of the marine sulfur cycle. In 1996, his fascination with new and unusual hydrothermal vent microorganisms brought him to WHOI, as a postdoctoral scholar with the late Holger Jannasch and then as assistant scientist in the Biology Department. At WHOI, he became interested in the diversity and biogeochemical activity of microbes living in massive seafloor sediment layers. Teske now pursues the emerging field of deep-subsurface microbiology at the Department of Marine Sciences at the University of North Carolina, but he and his family return to Woods Hole every summer to keep up collaborations, and to sample Woods Hole's famous microbial life.

Katrina Edwards grew up in central Ohio, where she pursued an initial career in the family business of running a small municipal airport just north of Columbus. She spent several years assisting her father and siblings in general airport operations (graduating to the role of chief flight instructor), which she continued as she pursued a bachelor's degree in geology at Ohio State University. Edwards then "retired" to attend the University of Wisconsin, Madison, where she earned a Ph.D. in geomicrobiology—the first degree in this field ever awarded by the university. Edwards and her family moved to Massachusetts in 1999 to join WHOI, where she established a geomicrobiology lab. It focuses on "the tooth decay of the solid Earth," she says, or more specifically, the transformation and degradation of Earth materials (rocks, minerals, organic matter) by microbes. Edwards now enjoys deep-sea exploration, as long as someone else "flies" the submarine and she can focus on geomicrobiological research.

B Tebo, Scripps Inst of Oceanography

Life in the Arctic Ocean

Distinctive species and environmental factors combine to create a unique, complex food web

By Carin Ashjian, Associate Scientist
Biology Department
Woods Hole Oceanographic Institution

Capped with a formidable ice and snow cover, plunged into total darkness during the winter, buffeted by blizzard winds, and bitterly cold, the Arctic Ocean is one of the most inaccessible and yet beautiful environments on Earth. Life here endures some of the greatest extremes in light and temperature known to our planet. Yet despite these inhospitable conditions, the Arctic Ocean is teeming with life.

Great polar bears roam the ice and swim the seas. These top predators are supported by a complex ecosystem that includes plankton, fish, birds, seals, walruses, and even whales. At the center of this food web, supporting all of this life, are phytoplankton and algae that produce organic material using energy from the sun.

The Arctic's extreme environmental conditions have limited our opportunities to study this complex food web. Expeditions to the remote Arctic are difficult and expensive. When we can get there at all, it is usually only in summer. Such gaps in our observations have compromised our ability to understand the food web's intricacies and vulnerabilities—at a time when the ecosystem appears to be increasingly vulnerable.

Scientists now know that warming temperatures are affecting the Arctic Ocean, producing changes that may have cascading effects on the Arctic's interlinked and delicately balanced food web. Changes in the food web not only threaten life in the Arctic region, they also could have impacts on Earth's climate. Populations of Arctic plankton, for example, not only provide food at the base of the food web, they also convert carbon dioxide from the atmosphere into organic matter

SHEBA Project Office

ICE CAMP—The Canadian icebreaker Des Groseilliers *was purposely frozen into the Arctic ice for a year in 1997-98 to create a tiny, isolated camp with outlying laboratory structures. Inset: Drifting within the ice, the ship traveled more than 1,739 miles (2,800 kilometers) in a year.*

that eventually sinks to the ocean bottom—effectively extracting a heat-trapping greenhouse gas from the atmosphere.

Life and light springs eternal

Every spring, after the long dark night of Arctic winter, the sun reappears over the horizon. Then, a cumulative sequence of events begins, and life in the Arctic springs into action.

With each day longer than the previous one, light begins to penetrate the thick cover of snow and ice to the undersurface of the ice, where ice algae begin to grow, like mold on a damp ceiling. One green, string-like form, *Melosira*, grows long, hanging under the ice like Spanish moss. It eventually detaches from the under-ice surface and sinks to the seafloor where it is consumed by the animals living there.

As days lengthen, light and warmth increase, and the winter snow cover that accumulated over the ice begins to melt. Once the snow melts, enough light can penetrate the ice to spur the growth of phytoplankton—very small, drifting, plantlike organisms that live in the water. They become available as food for higher organisms in the food web, the zooplankton—tiny marine animals that, in turn, are eaten by larger animals, from fish to jellyfish to whales.

A rich and vulnerable ecosystem

Nowhere are plankton ecosystems less understood than in the Arctic Ocean. Without more detailed knowledge about the workings of these ecosystems and the life histories of the individual life forms in them, we cannot predict how they will be affected by climate changes. But those changes already appear to be happening.

Scientists have documented dramatic shifts in Arctic ice cover, water temperature in the Arctic Ocean, and the atmosphere above it—all potentially due to the effects of a warming climate. Such changes are likely to affect, and may alter, the Arctic food web and ecosystem. They may change the amounts of water, nutrients, and plankton coming into the Arctic Basin, or change the timing of spring growth.


Carin Ashjian, WHOI

A QUARTET OF COPEPODS—The four major copepod species in the Beaufort Sea all have different sizes, different life cycles, and different prey. From left: Metridia longa *(~2.5 millimeters),* Calanus glacialis *(~4mm),* Calanus hyperboreus *(~7mm), and below,* Oithona similis *(0.5mm). The largest species,* C. hyperboreus, *is a critical link in the Arctic food web, eating phytoplankton and microzooplankton when returning light triggers their growth in the spring. They are eaten, in turn, by many larger animals.*

The great bowhead whale, for example, depends on plankton patches found along the northern coast of Alaska for food during its migrations between the summer feeding grounds off Arctic Canada and its overwintering grounds in the Pacific. Climate-induced changes in the availability of these plankton patches may have dramatic impacts on the whales, with either more or less food available along their migration route.

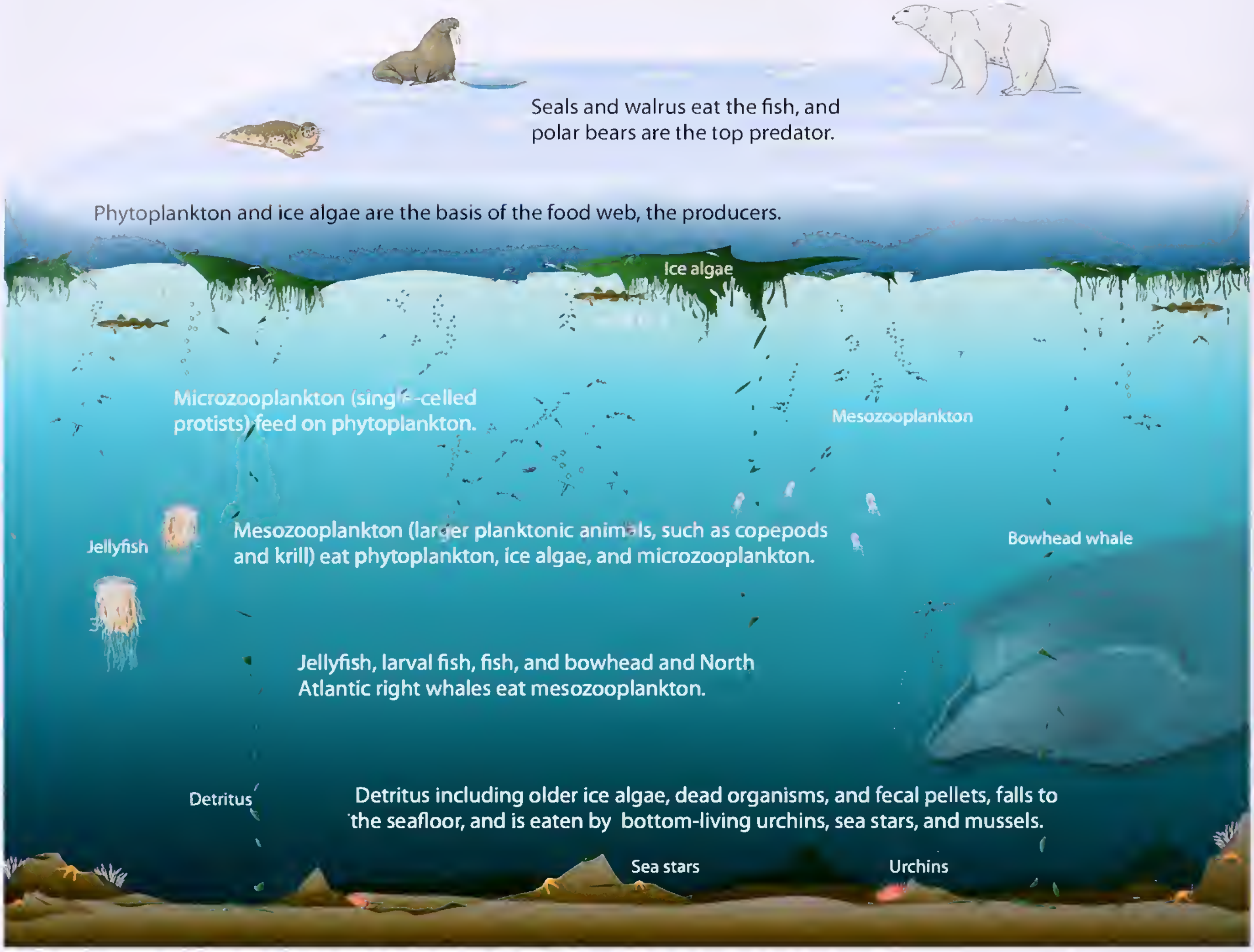
Populations of Arctic plankton are a conduit for the uptake, processing, and transformation of carbon dioxide. Warming-related changes in the Arctic environment, such as changes in ice cover, may have impacts on this planktonic conduit. Changes in the amount of carbon that flows and cycles through this food web will change the amount of carbon retained in the ocean or respired back into the atmosphere. These changes may fundamentally alter the structure of Arctic ecosystems.

The SHEBA ice camp

To begin to shed light on the dimly understood Arctic ecosystems and food webs, I spent parts of 1997 and 1998 living in the SHEBA (Surface HEat Budget of the Arctic) ice camp, a major science encampment both on and in the ice in the part of the Arctic Ocean known as the Beaufort Sea. I studied seasonal changes and life cycles of the Arctic plankton ecosystem.

The heart of the camp was the Canadian Coast Guard icebreaker *Des Groseilliers*—a big, bright red ship conspicuously and intentionally frozen into the ice for

The Arctic Ocean ecosystem



CARBON ALSO FLOWS THROUGH IT—The Arctic ecosystem's unique, complex food web is fashioned by its distinctive plankton, animal species, and environmental factors. Carbon also cycles through the web from atmoshere to seawater and back. Phytoplankton and algae take up carbon dioxide from seawater and transform it into the organic carbon of their tissue. Animals that eat the plankton convert their prey's carbon into their own tissues or into sinking fecal pellets. Along the way, some carbon dioxide escapes back to the atmosphere through the organisms' respiration.

the entire year. It served as a comfortable and opulent (for ice camps!) hotel and laboratory base. Separate labs were scattered on the ice surrounding the ship, housed in structures ranging from small tents to a 20-foot blue metal, bear-proof container, affectionately named the "Blue Bio," because it supported biological studies.

Leaving the ship for the labs held risks for the unwary. During summer months, we observed firsthand the effects of a warmer climate, as our stable ice platform melted into an impressive resemblance of Swiss cheese. Life jackets were required equipment when venturing off the ship onto the ice—in case we made a false step between the holes on our way to the labs. In addition, the threat of polar bears was very real, and all eyes were on watch at all times. Often, the tracks of visiting polar bears were visible in the snow in the morning. We had several opportunities to watch these fascinating creatures from the safety of our warm, red ship.

My studies focused on copepods—small (one to seven millimeters long) crustaceans that are a critically important link between phytoplankton and larger animals. I concentrated on four species of copepods that dominate the zooplankton community both in number and biomass (weight). Each has a different size, life cycle strategy, and role in the food web, marked by the quantity and type of prey that they consume.

Two of the species are fairly large members of the genus *Calanus*, which are believed to be omnivores (eating both plant-like phytoplankton and tiny animal-like microzooplankton). One medium-sized species, *Metridia*, is an omnivore and a voracious consumer of *Calanus* copepod

eggs and juveniles. The fourth is the extremely abundant and very small *Oithona*, also an omnivore.

An abundance of diverse life

At the SHEBA ice camp in1997 and 1998, I studied the abundance, reproduction, growth and development rates, and sizes of these four copepod species over their seasonal cycles with my colleague Bob Campbell from the University of Rhode Island. We verified that previous studies dating back to the 1950s through 1970s underestimated the biomass of zooplankton in the Arctic Basin. It may be as much as 10 times greater than we previously believed.

We confirmed that *Calanus* copepods live to be three years old, reproducing during the summer when food is plentiful. Two species (*Oithona* and *Metridia*) have more prolonged reproduction that extends over much of the year. The fourth species (*C. glacialis*) cannot successfully reproduce in the central Arctic, we think, so *C. glacialis* populations there must be brought in by currents from the surrounding Arctic shelves.

These different life histories may have important consequences for the species, and they give scientists new insights into understanding the species' chances to survive changing seasonal cycles or food availability that might occur with climate change.

Tracking who eats whom

In an ongoing project, Campbell, Eveleyn and Barry Sherr of Oregon State University, and I are exploring planktonic food webs in western Arctic shelves and basins. We are measuring the rates at which the tiniest animal plankton, called microzooplankton, consume Arctic phytoplankton. We then measure the rates at which the copepods (which are middle-sized plankton, or mesozooplankton) consume phytoplankton and microzooplankton. We also are investigating the food preferences of the different groups. Do copepods prefer a phytoplankton or a microzooplankton diet, for example? Do they eat ice algae?

Carin Ashjian, WHOI

A VIEW FROM THE BRIDGE—The bow of the research ship Des Grosielliers *points to a newly opened crack, or lead, in the melting ice, coated with a thin layer of freshly frozen ice.*

To do this, we conducted feeding experiments during two six-week cruises to the Arctic in the summer of 2002, on the U.S.C.G. *Healy*, the United States' newest icebreaker. First, we collected plankton by towing plankton nets to catch the copepods and determine their abundance in the water. In feeding experiments, we collect animals and seawater, select a known number of copepods, and incubate them with their prey to measure how much they eat in 24 hours.

Then we couple the grazing (feeding) rates of individuals with their abundances in the water to calculate the flow of carbon through the food web. This fundamental information is critical to our basic understanding of Arctic food webs, and it gives biological modelers the data they need to predict more accurately the potential impact of environmental and climate change on the fate of carbon in this ecosystem.

Summering in the ice

In the summer of 2004, we embarked on two more cruises on *Healy* to continue this work. We concentrated on investigating the potential of ice algae as a food source for copepods. We also documented whether one of the copepods (*C. glacialis*) can reproduce using its stored fat alone, or whether it requires available food.

Every trip to the largely unexplored Arctic seas brings new challenges, surprises, and insights for researchers. Every trip also contributes to our understanding of this remote, severe, but very active ocean and its role in sustaining life on Earth.

Peter Lane, University of Miami

Growing up in Massachusetts, Carin Ashjian became interested in the ocean during summer vacations spent on Buzzards Bay. She studied biology at Cornell University and then specialized in oceanography, receiving a Ph.D. from the University of Rhode Island. Her interest in polar regions was sparked by two cruises to the Arctic during postdoctoral positions at Brookhaven National Laboratory and the University of Miami. She moved to WHOI in 1995, and has pursued her interest in polar research since then, working first at the SHEBA ice camp in the Beaufort Sea. More recently, she has divided her research time between the Antarctic continental shelf and the shelf-basin boundary of the Chukchi and Beaufort Seas in the Arctic, studying the ecology of polar zooplankton. On average, she spends three months per year at sea. On those occasions when she gets tired of the ocean, she spends time inland picking apples or making maple syrup. In 2005, she begins a new project in the Arctic to investigate the cascading impacts of climate variability on oceanography, plankton distributions, bowhead whale migrations, and Iñupiat subsistence whaling.

Shedding Light on Light in the Ocean

New research is illuminating an optically complex underwater environment

By Sönke Johnsen, Assistant Professor
Biology Department, Duke University
and Heidi Sosik, Associate Scientist
Biology Department
Woods Hole Oceanographic Institution

Light in the ocean is like light in no other place on Earth. It is a world that is visibly different from our familiar terrestrial world, and one that marine animals, plants, and microbes are adapted to in extraordinary ways.

Light behaves very differently when it moves from air into water. It moves through the expansive depths of an ocean that is devoid of solid surfaces. These and other factors combine to create an environment that has no equivalent on land.

A scuba diver in the open ocean discovers she is immersed not only in water, but also in an ethereal blue light. Seawater absorbs light much more strongly than air does, but visible light is made up of a rainbow of different wavelengths, each perceived by humans as a different color. Blue light penetrates farther into seawater (giving the ocean its distinctive color). At the same time, seawater absorbs red, orange, and yellow wavelengths, removing these colors. Only a few meters below the sea surface, if our diver looked into a mirror, she would see that her red lips appeared black.

In calm weather, the diver can look upward to see the entire hemisphere of the sky compressed into a circle over her head—a phenomenon called Snell's window, caused by the bending of light as it enters water. Rough weather and waves shatter this window. The waves act like lenses to focus light, creating a scintillating visual field whose brightness increases and decreases by a factor of a hundred as each wave passes by, making it impossible for eyes to adjust.

If our diver wore ultraviolet (UV) viewing goggles, almost half the light she would see looking down and horizontally would be UV. Light passing through water also becomes polarized, which means its wave motion vibrates in only one direction, or plane. (This also happens to the light reflected as glare from the sea surface or a wet road.) If our diver wore sunglasses that blocked horizontally polarized light (light vibrating in the horizontal plane) and looked to her side, her view would be dark. But if she looked up or down, her view would be full of light, because the sunglasses would allow light vibrating in the vertical plane to pass through.

Laurence Madin, WHOI

A scuba diver in the open water is immersed in clear, pure blue light. Water strongly absorbs red, orange, and yellow light, while blue light penetrates to the depths.

Light frames life

In many ways, light permeates and creates the environment that ocean organisms experience. The same is true on land—though we often take light for granted. We see light as background, when it actually sets the stage and dictates our view of the world. As sure as day follows night and the sun makes plants grow, light frames our existence.

So it is, too, in the ocean, where animals and plants are bathed in different kinds of light coming from all directions, in a way we land-dwellers never experience. Some animals possess visual systems that see ultraviolet and polarized light (which people cannot) and have clever strategies to avoid detection in an environment where one can be seen from every angle and there is nothing to hide behind. Even in the sunless depths, light still plays a crucial ecological role, with armadas of bioluminescent life making and using their own light.

Humans have had limited ability to explore the dimension of light in the ocean. Today, however, new technology promises to reveal how light operates to create assorted phenomena and a unique ocean environment that ocean life is adapted to.

Wavelengths in the waves

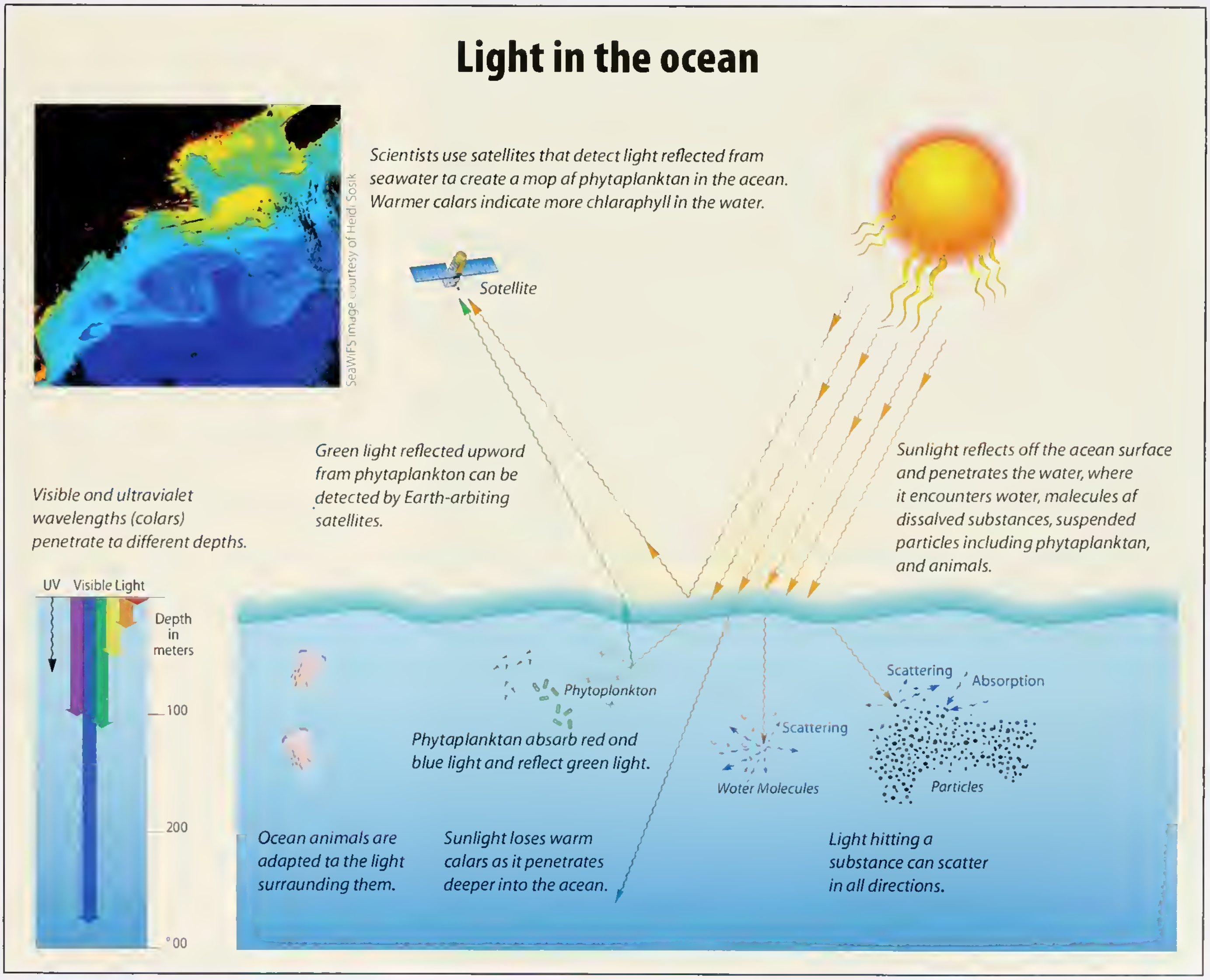
When light hits a substance, it can do one of three things: It can be scattered, by hitting molecules of the substance and bouncing off in different directions; it can pass through the substance; or it can be absorbed by the substance—either wholly or in only some wavelengths. Much sunlight reflects (scatters) off the ocean, but much also penetrates it and is absorbed by seawater. Several hundred miles from shore, our diver sees extraordinarily clear and pure blue water because water in the open ocean has low concentrations of dissolved matter and particles, such as phytoplankton. It does not scatter and absorb as much light as murkier coastal water does, and the light that remains is blue.

Nearer the coast, light penetrating seawater provides the energy to fuel vast photosynthetic hordes of microscopic marine plants—phytoplankton—which are an essential source of food and oxygen for the entire planet. Just below the surface, our diver will see green light, depending on how much phytoplankton is present. Water with high concentrations of phytoplankton is green and darker for the same reason that dense tropical forests are: Plant pigments absorb blue and red light and reflect green light, and the cells scatter the light more than pure water does. While the diver would not be able to detect microscopic phytoplankton cells, she would see their cumulative effect on the light in the ocean.

Providing the oxygen we breathe

Beyond their impact on light, marine phytoplankton also have enormous impact on our planet. Photosynthesis by these abundant cells produces roughly half the oxygen in our air.

Phytoplankton have evolved the ability to use the blue and green light found



Jayne Doucette, WHOI Graphic Services

Adaptations to light, from surface to depths

The dark backs and light undersides of these near-surface fish help them match their environment in the open ocean. To a predator looking from above, their dark backs seem to blend into the dark depths. From the side, their lighter sides blend with the sunlit water.

Many open ocean animals use invisibility to hide in plain view. Adapted to limitless, featureless blue surroundings, this planktonic ctenophore, Cestum, *lives near the ocean surface. The complete transparency of its body makes it almost impossible to see against the open ocean waters.*

The hatchet fish is well prepared for the midwater ocean's light levels. Bright silver sides reflect whatever light surrounds it. Long, tubular eyes capture and detect low light levels. Living at depths from 200 to 1000 meters, it has ventral (underside) light organs that can produce bioluminescence to match light coming from above, making it less visible from below.

With enormous upward-looking eyes that fill half its otherwise transparent body, the deep-living shrimplike amphipod Cystisoma *is well-suited to its dim world. It needs such large eyes to detect the little light available in its midwater environment (800 meters). At that depth, red eyes appear black—and invisible.*

Atolla *is a jellyfish common from midwater, about 500 meters deep—where there is still a small amount of sunlight, to depths of 4,500 meters—far below the limit of sunlight's penetration. Where there is light, its red color looks black, making it hard to see. It also produces brilliant bioluminescence, possibly to frighten predators.*

Images courtesy of Laurence Madin, WHOI

in the ocean. If water were not relatively transparent to this light, aquatic photosynthesis would not be possible, and the ocean would be largely a dead zone. In addition, if coastal waters become less clear because of human activities, photosynthesis by phytoplankton may decrease.

Phytoplankton form the base of the prolific marine food chain, which ultimately also helps feed people and other terrestrial life. Throughout Earth's history, phytoplankton have also played an important role in regulating Earth's climate. They remove huge amounts of the greenhouse gas carbon dioxide from the atmosphere, turning it into organic matter via photosynthesis. Much of this organic carbon is consumed by animals in upper ocean waters. Some falls to the seafloor, as dead organisms or fecal pellets, where it is consumed or converted over time into oil and gas deposits.

The threat of UV radiation

Marine photosynthesis is confined to the tiny fraction of ocean where sunlight penetrates—at most, the upper 200 meters. UV light also penetrates this region, which may have increasingly profound consequences. UV radiation can cause damage to organisms on both land and sea. Recently, scientists have discovered that ultraviolet radiation can harm organisms deeper than previously thought.

Decreasing ozone levels in the atmosphere, including the ozone hole over Antarctica, may exacerbate the problem, because ozone blocks UV radiation from reaching Earth. Higher levels of UV can kill phytoplankton, slow their growth, or disrupt the delicate balance of species that interact in ocean ecosystems.

Marine organisms have evolved ways to protect themselves from UV. These include UV-absorbing pigments, the ability to repair UV-damaged DNA, and developing behavior to avoid UV by staying in deeper water. However, the recent ozone changes may be occurring too fast for organisms to adapt. Given the fundamen-

tal role of phytoplankton in Earth's biology, chemistry, and climate, these changes may affect us all.

Into the darker depths

As our diver continues to descend a few more meters, she begins to go from day to night. She can see blue light to her sides, and white light above, but below her the view is dark. As she moves downward, the UV, green, and violet wavelengths disappear, and the light becomes an intense, almost laser-like, pure blue. At 200 meters deep, the diver would cross from the surface realm (called the epipelagic zone), where there is enough sunlight for photosynthesis, to the twilight realm (called the mesopelagic zone), where enough sunlight penetrates for vision, but not for photosynthesis.

By now, our descending diver would notice nearly continuous blue flashes around her—bioluminescent light produced by animals in the midwater zone, in response to the disturbance in the water that she caused. Below 850 meters, though, the diver would no longer be able to see anything, even looking up. Human eyes aren't sensitive enough to detect the minute amounts of sunlight that haven't been absorbed by the water. At 1,000 meters, even the most visually sensitive deep-sea animals can no longer see the sun. The region below this is known as the aphotic (no-light) zone, but this is only true for sunlight, as bioluminescence is common.

Predators—using light to hunt

Not surprisingly, aquatic animals possess visual systems that are specially adapted to the nature and properties of light underwater. Animals living near well-lit surface regions have eyes similar to terrestrial species. They have color vision, since light near the surface still has color.

Many also have UV vision, which advantageously extends their range of vision. Many animals contain compounds in their tissues that protect them against UV radiation by scattering, reflecting, or absorbing UV light. This makes the animals appear dark and silhouetted against an otherwise bright background of UV light. With UV vision, animals can see animals that are transparent in visible light.

Some ocean animals, such as shrimp and squid, can even see the polarization of underwater light—due to a special geometric arrangement of their retinas. With this ability, they can actually navigate by the skylight polarization pattern, or detect otherwise transparent, or silvery-scaled prey by seeing its effect on the polarization of light.

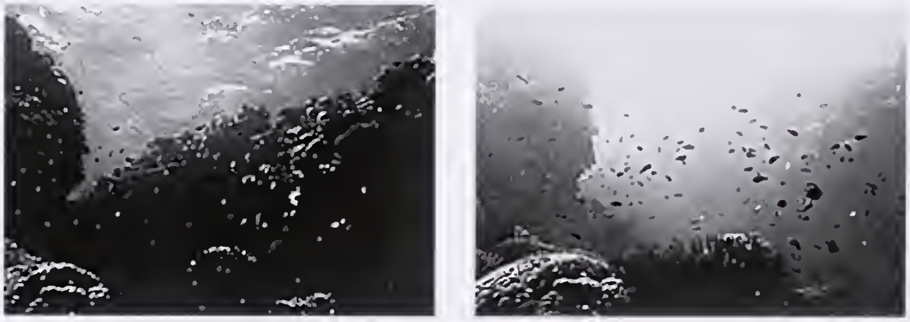
In deeper, mesopelagic regions with less light, the animals often have bizarre adaptations to increase their visual sensitivity. They see in extremely low light levels, though at the expense of acuity, with a reduced ability to detect rapid movements. Long, tubular, telescope eyes in fish, or enormous crustacean eyes that fill the animal's entire head capture as much light as possible.

Prey—using light to camouflage

But seeing is only part of the equation. Ocean organisms' visual adaptations are matched by clever strategies to avoid being seen in an open ocean where it is difficult to hide. Some color themselves to match the background water. Others have mirrored sides, because a mirror in the ocean only reflects more of the ocean, and so is invisible.

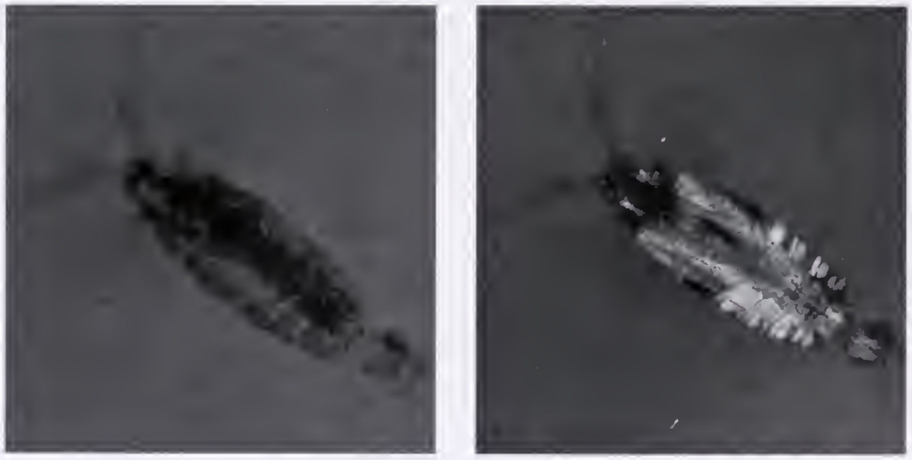
Still others camouflage themselves with light, hiding their silhouettes with light-producing organs on their downward-facing surfaces that mimic the surrounding illumination. Many are simply transparent, matching their background in all situations.

Finally, some use light and dark for



Courtesy of Tom Cronin

The advantage of UV vision shows in reef views in visible (left) and ultraviolet (right) light. In UV light, the fish are in much higher contrast to the background.



Courtesy of Nadav Shashar

Prey species such as the copepod Labidocera *are nearly transparent in visible light (left), but they are brightly visible when photographed in polarized light (right), or to a predator that can see polarization of light.*

disguise. They hide in the depths during the day, rising to feed at night, or they stay near the surface, hiding in the glittering background of the lensing waves.

Instruments to measure light

To study light in the sea, scientists use a wide range of instruments—submerged in the depths and sent into space. Submersible radiometers, or light meters, measure ultraviolet and visible light and detect extremely low light levels in the deep sea. They numerically describe the shape of the light field in the ocean and measure how light is absorbed and scattered in water over small spatial scales. They can be lowered from ships, placed on submersible vehicles, or even carried by scuba divers to investigate the optical environment of specific areas or depths.

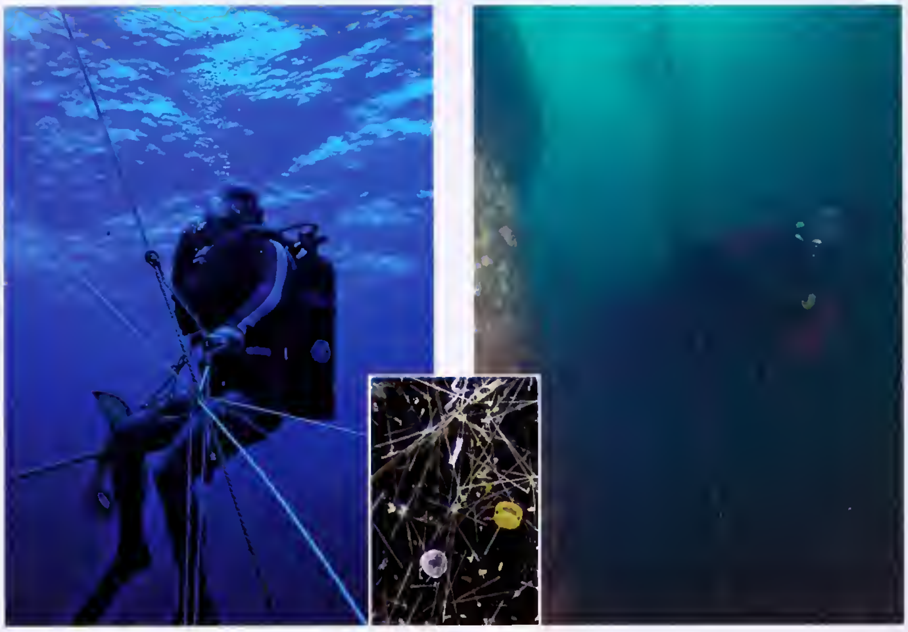
One of the most exciting advances in oceanography has been the developing ability to measure changing color over wide swaths of the ocean, using Earth-orbiting satellites that carry spectral radiometers that measure light reflected from the surface of the ocean. These color changes indicate changes in the global distribution of phytoplankton. For the first time, oceanographers can see how phytoplankton populations bloom, collapse, and change over time in any area, and these satellite views have revolutionized how we think about the upper ocean.

A bright future

Despite continually improving satellite data, optical oceanographers still have too few observations. Satellites view only the upper few meters of the water. With underwater instruments, we can sample only relatively few specific places and times in the ocean. What's lacking is a way to visualize the entire ocean—surface to depths and across the globe.

Computer models offer a way to approach this deficit. Combining available observations with new, accurate computer models that simulate how light behaves and propagates through the ocean has led to insights on satellite-based ocean color measurements, global phytoplankton productivity, and how marine animals use light and camouflage.

The door is now open to answering questions about the operation of light in the ocean, and its role in the lives of marine phytoplankton and animals. We are gaining new understanding of this heretofore shadowy—but not lightless—realm.

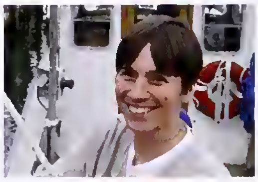


Left photo and inset by Laurence Madin, right photo by Terry Rioux, WHOI

DIVING INTO DIFFERENT WORLDS—Open ocean water (left) contains few particles and absorbs warm colors, so blue light penetrates far into the clear distance. Near the coast, high nutrient levels allow dense growth of phytoplankton (center), making the water appear green and darker (right). Forests appear dark and green for the same reason—plant pigments absorb red and blue wavelengths of light and reflect remaining green light.

Steven Haddock, MBARI

Sönke Johnsen entered biology with backgrounds in math, physics, and art and has since used all three fields to investigate the visual ecology of oceanic zooplankton. After a frustrating graduate career, in which he studied the vision and behavior of animals with neither eyes nor brains, he completed postdoctoral fellowships at Harbor Branch Oceanographic Institution and WHOI. After a year as an assistant scientist at WHOI, he accepted a position in the Biology Department at Duke University. He is interested in all aspects of vision in oceanic species, with a particular emphasis on strategies for camouflage. The camouflage research has involved investigations into UV vision, whole-body transparency, cryptic coloration, and counterillumination using techniques ranging from blue-water diving to protein biochemistry to Monte Carlo modeling of photon trajectories. He gives numerous talks to the general public and his work has been featured in newspapers, magazines, and a John Updike poem.



Tom Kleindinst, WHOI

Heidi Sosik received bachelor and master of science degrees in Civil and Environmental Engineering from MIT in 1988 and a doctorate in oceanography from Scripps Institution of Oceanography in 1993. She joined the Woods Hole Oceanographic Institution as a postdoctoral scholar in 1993 and is now an associate scientist in the Biology Department. Her research interests focus on phytoplankton ecology and factors that influence light in the marine environment. She received a Presidential Early Career Award for Scientists and Engineers in 1996 and is currently a joint Fellow of WHOI's Ocean Life Institute and Coastal Ocean Institute. "Never a dull moment" is an apt description of life for Heidi, whose family—one husband, three kids, two dogs, and a cat—keep her keel even and her sails full through the ups and downs of a career as an oceanographer.

Whither the North Atlantic Right Whale?

Researchers explore many facets of whales' lives to help a species on the edge of extinction

Michael Moore, Research Specialist
Biology Department
Woods Hole Oceanographic Institution

For millions of years, the North Atlantic Ocean has been home to right whales. In winter, they gave birth to calves off the shores of West Africa in the eastern Atlantic and off Florida and Georgia in the western Atlantic. In the spring, they migrated north along the coasts as far as the Gulf of St. Lawrence and the seas north of Iceland to feed in plankton-rich northern waters in summer and fall.

In 1150 King Sancho the Wise granted privileges to Navarre, a Basque province in northern Spain, to charge a duty on whalebone. So began centuries of whale hunting in which tens of thousands of right whales on both sides of the Atlantic were killed.

Today only a remnant of the population survives, no more than 350 whales clustered in calving and feeding grounds along the eastern seaboard of North America. Only occasional right whale sightings in the Gulf of St. Lawrence or in the waters between Iceland, Greenland, and Norway give echoes of their once substantially greater range.

To help a vulnerable population

Since whaling ceased in the 1930s, related and similarly decimated species, such as the Southern Ocean right whale, have demonstrated spectacular recoveries. However, the North Atlantic right whale population has not rebounded.

Too few are being born. Too many are dying—often in accidents induced by human activities such as shipping and fishing. In 1999, a study by Hal Caswell of Woods Hole Oceanographic Institution, Solange Brault of the University of Massachusetts, and then-MIT/WHOI graduate student Masami Fujiwara warned that unless this dire trend is reversed, the species is headed toward extinction.

But to know how to help this dwindling population, we need to know much more about the factors preventing its recovery. We need to learn much more about the lives of whales, whose vast watery domain has made them far more difficult and inaccessible to study than terrestrial animals.

"The Hunt" (American School), Courtesy of The Boston Art Club

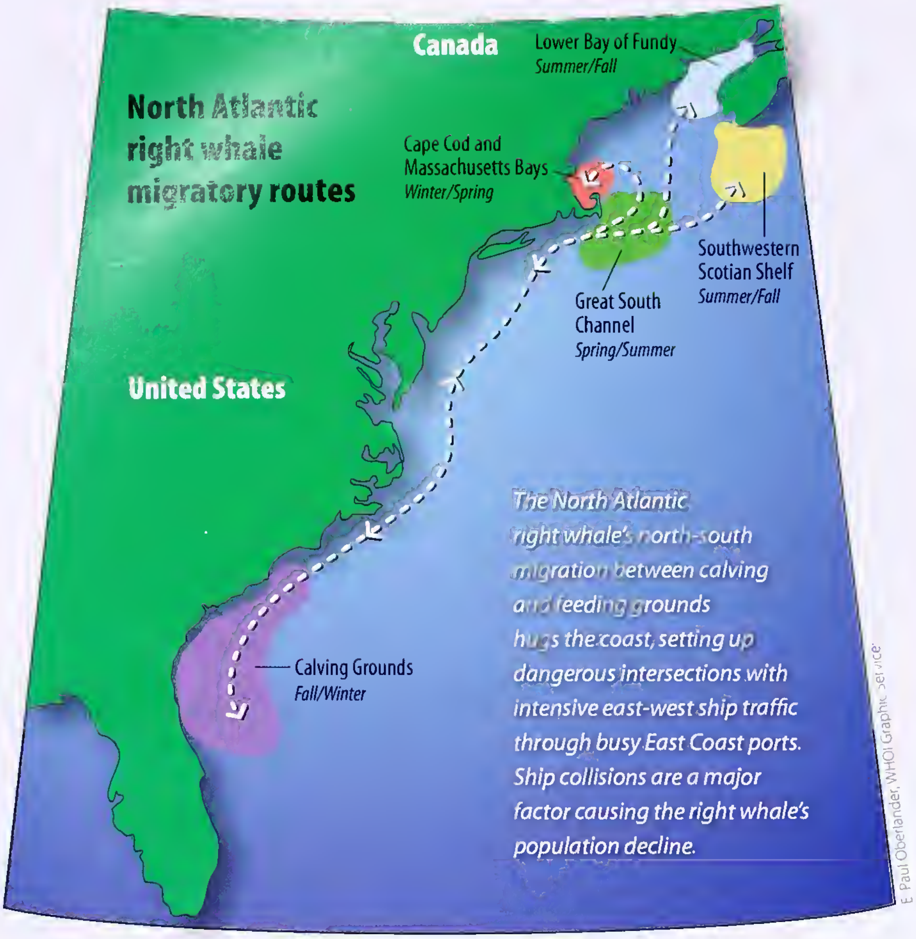
Slaughtered over centuries

Right whales dwell along coastlines, which has always made them convenient and vulnerable to whalers. The Basques were granted the right to levy a tax on whale products and began hunting them in 1150. They continued for nearly 600 years.

By the 1500s, Basque whalers had exterminated the right whale population on the eastern side of the North Atlantic Ocean, and too few whales remained for worthwhile hunting. In the latter part of the 16th century, they expanded their hunting grounds westward, particularly to the waters off southern Labrador.

Then New England shore-based whalers took over, seeking oil and baleen for energy and commercial products. Their catches peaked in the early 1700s, but high-seas Yankee whalers continued to pursue this species whenever opportunity afforded.

Even into the 20th century, right whales were hunted near Iceland and Scotland. The last animals to be taken intentionally were a mother and calf off Madiera in 1967, although they had been protected from hunting since 1935.



The North Atlantic right whale's north-south migration between calving and feeding grounds hugs the coast, setting up dangerous intersections with intensive east-west ship traffic through busy East Coast ports. Ship collisions are a major factor causing the right whale's population decline.

Now researchers are working together, using a variety of new techniques and instruments, to study the whales' habitats, health, physiology, endocrinology, and genetics; their mating, feeding, and diving behaviors; their migration patterns and routes; their response to sounds, and their population changes over time. This basic knowledge can provide the foundation to devise efficient and effective management and conservation strategies that can enhance the species' chances of survival.

Too many deaths

A critical factor in the North Atlantic right whale's decline is human-induced mortality, caused by collisions with ships and by entanglement in fishing gear. Unlike the recovering Southern Ocean right whale population, which travels in far less populated and trafficked waters, North Atlantic right whales are exposed to gauntlets.

The right whales' north-south migration between calving and feeding grounds sets up a dangerous intersection with intensive east-west shipping traffic through many of the world's busiest ports on the North American East Coast. Resulting collisions cause fatal trauma to whales, including propeller lacerations and fractured jaws, brain cases, ribs, and vertebrae. Ship collisions kill an average of two North Atlantic right whales per year, though more undocumented fatalities probably occur.

East Coast waters are also prime fishing grounds. Right whales run into fixed lobster, crab, and other trap fishery gear, and anchored gill nets. They get fishing lines around their tails, flippers, or in the worst-case scenario, through their baleen plates as they filter water for long periods with their mouths open. As they struggle, the whales' flippers, bodies, and tail stocks can get wrapped in ever tighter circles. Many right whales can free themselves from less severe entanglements, but others can't. They may die rapidly, or swim for months with the gear attached, only to die several months later.

Swimming in traffic

Reducing collisions between ships and whales is enormously difficult. At times, right whales appear to be unable to detect, or at least to avoid, large ships. We don't know as much as we need to about the physiology of whales' ears and what they can hear.

At WHOI, scientists Darlene Ketten and Susan Parks have done seminal research on right whale hearing. (See "How to See What Whales Hear," page 59.) To investigate the behavior of right whales in response to noise, WHOI biologist Peter Tyack and his colleagues have developed sophisticated digital, suction-cupped tags that can be placed temporarily and harmlessly on the whales. (See "Run Deep, But Not Silent," page 54, and "Playing Tag with Whales," page 57.) The tags record the whales' diving, surfacing, and swimming movements in response to ships, natural noises, and alarm stimuli—the latter in the hope that some system to warn whales of approaching ships could be developed.

Are the whales so habituated to ubiquitous ship noise that they don't distinguish ships? Do ships exert hydrodynamic forces as they travel through water, which the whales are unable to evade? More research must be done to answer these fundamental questions.

There has been one significant recent advance in the effort to reduce ship strikes. Moira Brown of the New England Aquarium (NEAq) in Boston, and a group of collaborators from industry, science, and government in Canada, have made it possible to relocate a major shipping lane away from a prime right whale habitat in the Bay of Fundy. In addition, efforts have begun to educate international maritime professionals to the risk

of whale-ship strikes, and ships traveling in right whale habitats in U.S. waters are now required to report whenever they are transiting such waters.

Lethal entanglements

There are only two ways to mitigate the fishing gear problem: reduce the number of whales entangled or disentangle animals seen trailing fishing gear.

Disentanglement efforts, led by the Provincetown Center for Coastal Studies (PCCS), have at times been spectacular but will never be a solution. Numerous animals have been successfully disentangled, using modified small-boat whaling methods to slow down the animals and make strategic cuts in entangling gear. But despite heroic efforts and the development of physical and chemical restraint systems, a significant number of cases have been intractable: The whales were impossible to free, and they died.

Even the best disentanglement technique will never remove the ongoing flow of new cases. Many of these are only evident in new rope scars on previously unscarred individuals. Avoiding entanglement is the true solution and a critical current research focus.

Researchers in academia, government, and industry are all seeking modifications to fishing gear that attempt to decrease or eliminate entanglement. These include developing weak links in fixed fishing gear so that lines break rather than obstruct a colliding whale, and changing the buoyancy of lines to reduce their exposure in areas where whales dive. Other potential modifications include gear with less friction to reduce abrasion and laceration with whale flesh, and with better visibility, so that whales have a better chance of avoiding them. Some seasonal fishing regulations have also been established with the aim of minimizing encounters between right whales and fixed fishing gear.

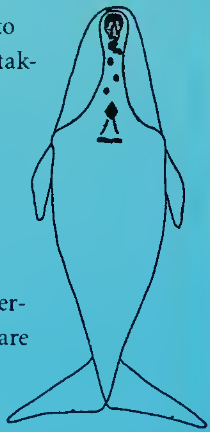
None of these efforts has yet decreased the mortality rate. Most are controversial because commercial fishermen question

Photo courtesy of the New England Aquarium

Scientists distinguish individual right whales by black horny protuberances on their heads, called callosities, which are highlighted by intensely colored whale lice.

Distinguishing a "face" in a crowd

We know how many North Atlantic right whales exist, where they go, and even the life histories of individuals in the population because of four decades of research. This has included extensive efforts to photograph the population in boats and airplanes, and painstaking record-keeping.



WHOI biologists Bill Schevill and Bill Watkins launched modern-day studies of the North Atlantic right whale population in the 1960s with aerial surveys of whales in Vineyard Sound, Cape Cod Bay, and the Great South Channel off Nantucket. They and other whale research pioneers began to distinguish individuals by using distinctive, black horny protuberances, called callosities, on the whales' heads. The callosities are highlighted by intensely colored whale lice.

Photographs of callosity patterns and other distinctive body scars allow us to recognize individuals. Over the past 25 years, colleagues at the New England Aquarium and the University of Rhode Island, led by Scott Kraus and Bob Kenney, have catalogued right whale sightings from a broad consortium of institutions and individuals to build uniquely detailed databases that include individual histories for the majority of whales in the remaining population.

These databases include information on individual whale sightings, feeding, calving, toxic chemical exposure, genetics, and deaths. This shared database provides researchers with essential, fundamental information that undergirds most ongoing North Atlantic right whale research.

Like fingerprints, callosity patterns (in drawing above and real life below) give researchers the ability to identify and keep track of the life histories and movements of individual whales.

Photo and drawing courtesy of the New England Aquarium

the value of required changes and the selection of restricted fishing areas.

Too few births

Part of the shortfall of North Atlantic right whale population growth is a reproductive failure: Not enough calves are born.

Over recent decades, researchers have observed several disturbing trends: Mature females are having a declining number of calves. About 25 percent of mature females have never been sighted with calves. The age at which females have their first calf appears to be increasing. Intervals between pregnancies have increased. Overall, the species' calving rate is about one-third what it should be, which is all the more distressing in an already small population subjected to other stresses.

Once again, the inherent difficulties of tracking, monitoring, and sampling such large animals over a vast, remote region has limited our ability to understand why the North Atlantic right whale reproduction is so inconsistent. Suspected, and probably interrelated, causes include disease, pollutants, and poor food supplies.

Only recently, Rosalind Rolland at NEAq and colleagues have developed pioneering techniques to analyze whale fecal samples to obtain previously unobtainable biomedical data on whales. These are providing a novel, non-invasive window to reveal the whales' genetic makeup and their levels of contaminants and hormones (both reproductive and stress).

These biomedical data, along with other studies of whale body conditions and nutrition, will help assess the myriad factors that may be compromising right whales' health and ability to reproduce. Recent studies by my colleague Carolyn Miller and me, for example, indicate that Southern Ocean right whales may have higher birth rates than their northern cousins because they have better food resources and higher body fat reserves.

Protecting feeding grounds

The issue of nutrition leads directly to questions of whale food supplies: Where are they and how might they be protected?

Much of the research and management of North Atlantic right whales in U.S. waters today is driven by the federal Endangered Species Act and the Marine Mammal Protection Act. Independent, federal, and state agencies currently carry out large-scale annual surveys to count right whales and find where they go in which season.

The surveys show year-to-year variation in the whales' travel patterns, which scientists think are governed by differences in food availability. Whales, like other animals, follow their food. They feed on dense patches of zooplankton, especially small crustaceans called copepods. They strain mouthfuls of water through a fibrous filter in their mouths, known as baleen, which retains copepods that the whales swallow.

Right whales today feed in the Great South Channel, Cape Cod Bay, the Bay of Fundy, and the banks south of Nova Scotia. But there must also be other important feeding areas of which we are unaware.

Stormy Mayo of PCCS has demonstrated a critical need for conserving habitats where copepod patches are dense, such as in Cape Cod Bay in the winter and early spring. The location of these patches is probably determined by myriad factors: local phytoplankton productivity, the presence of other copepod predators, local oceanographic features, such as water temperatures and fronts separating different water masses—all of which may, in turn, be affected by climate changes

Courtesy Florida Wildlife Research Institute, taken under NOAA-Fisheries permit 932-1489 with authority from the U.S. Endangered Species and Marine Mammal Protection Acts. Photographer: Katie Jackson (FWRI)

LIBERATING LEVIATHANS—A rescue team from the Provincetown Center for Coastal Studies attempts to free a right whale with fishing lines wrapped around it. Fishing gear entanglements kill a significant number of North Atlantic right whales.

GENERATIONS NOT FORTHCOMING—Fewer new North Atlantic right whale calves are being born, threatening the species' ability to survive. Scientists seek to understand the reasons for their low and inconsistent birth rate, which may be linked to pollution or declining food supplies.

from year to year, or over decades.

WHOI biologist Mark Baumgartner and colleagues have begun to explore the factors that govern where, when, and why whale prey aggregates. Using tags and sensors, they have been collecting and correlating data on copepod abundances, oceanographic conditions, and whale feeding and diving behaviors. This fundamental knowledge on whale habitats is an essential first step to devise strategies to manage and protect them.

"Whale-safe" consumer products

Current and planned research at WHOI and elsewhere is aimed at several research fronts. (See "Scientists Muster to Help Right Whales," page 34.) Seeking ways to reduce human-caused deaths, researchers are analyzing the factors that prevent right whales from avoiding ships, and they are working to develop whale-friendly fixed fishing gear. They are gaining better understanding of the role of nutrition, chemical exposure, and infectious agents in reproductive success. And they are using computer models of right whale demographics to pinpoint the most critical factors, among many, that threaten the species' survival. This information, in turn, helps identify the most effective conservation strategies.

Will all this effort result in saving the North Atlantic right whale? Possibly. It depends largely upon our society's will to do what it takes to reduce human-induced whale deaths. This will involve very hard decisions. Major maritime industries will have to alter their practices in a way that our consumer-driven society is loath to allow.

An important and successful model to follow is that of the tuna fishery in the eastern tropical Pacific in recent decades. Tuna fishers used to target tuna by setting their nets around groups of dolphins. Overwhelming public opinion against this practice made the cost of "dolphin-safe" tuna acceptable.

If we can develop the same willingness to pay for right-whale-safe shipping and fishing practices, then the North Atlantic right whale has a chance to survive. The job facing the science and engineering community is to develop the tools and knowledge necessary to enable a "whale-safe" stamp on all lobster claw bands and other fishing products and on products shipped in containers and tankers to North Atlantic ports.

It's a Herculean task, and it could lead to much higher consumer costs. But the alternative is acceptance that humans exterminated a great species that plays powerful roles in human history and the natural history of the ocean.

Michael Moore grew up in England, where he trained as a veterinarian. He began his career as a marine mammalogist, concurrently in Newfoundland and the Caribbean. Moore then pursued his wife-to-be, Hannah, back to her New England home. He spent two years acquiring U.S. veterinary licenses, before gravitating to Woods Hole in 1985, where he was first at the Marine Biological Laboratory and then at WHOI. As a WHOI/MIT Joint Program student in the laboratory of John Stegeman in the Biology Department, his research first focused on tumors in flatfish exposed to Boston Harbor sewage. His interest therein endures, but since becoming a research specialist at WHOI, it has expanded to encompass other man-made impacts on marine vertebrates such as right whales and other marine mammals. He is also the veterinarian for the Cape Cod Stranding Network, which responds to single and mass strandings of marine mammals on Cape Cod.

Scientists Muster to Help Right Whales

With time running out, an ambitious research plan is launched for an endangered species

Laurence Madin, Director
Ocean Life Institute
Senior Scientist, Biology Department
Woods Hole Oceanographic Institution

It is a sad irony that we have cataloged individual photographs of the remaining North Atlantic right whales and given each of them unique numbers and sometimes names, yet we still know too little about their physiology, behavior, and habitats to take effective steps toward ensuring their survival as a species.

Rapaciously hunted by humans over centuries, the North Atlantic right whale has not recovered in the decades after whaling was outlawed. Living near heavily populated coasts, the whales are vulnerable to high levels of shipping, fishing, noise, and pollution. (See "Whither the North Atlantic Right Whale? page 29.)

Today, right whales lie at a critical crossroads in their long history—pointed dangerously toward extinction by the end of the century. Now, an ambitious program of intensified research has begun finding ways to aid them.

A species on the edge

We now know that the mission is possible. Using extensive right whale data collected by government agencies, researchers, and dedicated private groups, WHOI biologist Hal Caswell and colleagues analyzed the factors contributing to the species' population decline. Saving just two females per year from untimely death, they concluded, can reverse the downward trend and put the population on a road to recovery.

But despite years of research on right whale habits and habitats, we still lack practical ways to reduce deaths or increase births. Learning the secrets of huge and uncooperative animals that can be studied only fleetingly at sea or dead on a beach is a daunting task.

In November 2003, the WHOI Ocean Life Institute (OLI) convened a research forum in Woods Hole, gathering scientists and engineers from several institutions, along with representatives from government and industry, to assess the status of the North Atlantic right whale. Blending a diverse range of complementary expertise, they devised a collaborative research plan to accelerate advances in our knowledge of right whales. The OLI Right Whale Research and Conservation Initiative complements other government and academic programs, supplying essential pieces of the North Atlantic right whale puzzle they don't address. It will provide a necessary scientific foundation to guide effective conservation efforts.

Michael Moore, WHOI

A DIVE TO SURVIVE—A North Atlantic right whale dives in search of food near Grand Manan Island in the Bay of Fundy, Canada.


Vincent DeWitt Cape Cod Times

HIT BY A SHIP—A necropsy of this 50-ton, 45-foot right whale, washed onto a beach in Wellfleet, Mass., in 1999, showed a broken jaw, fractured vertebrae, and internal bleeding. The whale, known to researchers as Staccato, had given birth to many calves. Research has shown that saving just two mature females per year from untimely deaths could reverse the decline of the North Atlantic right whale population.

Joining forces

Over the next several years, scientists from WHOI, the New England Aquarium in Boston, the Provincetown Center for Coastal Studies, Trent University in Canada, and other institutions will join in the OLI Right Whale Research and Conservation Initiative. They are planning, launching, and seeking funds for a variety of studies aimed at:

- reducing accidental whale deaths caused by ship collisions and fishing gear entanglement
- understanding critical factors affecting right whale habitats, nutrition, reproduction, and health
- monitoring the North Atlantic right whale population to assess its size, present state, and future viability.

Right Whale Initiative strategies include pioneering studies of whale hearing, using CT scans to obtain physiological data on whale ears (See "How to See What Whales Hear," page 59), and field work to study whales' response to noise. Other scientists will use whale bone forensics to provide basic information on the speeds and masses of vessels that are unvolved in fatal ship-whale collisions. Another study will explore hydrodynamic forces, caused by ships moving through water, that lead to collisions.

Scientists will also test new types of fishing gear designed to slip off more easily and break when entangled whales try to free themselves. A remote control device is being developed to deliver sedatives and medications to entangled whales, to improve our ability to disentangle them.

A multi-pronged research effort

Over the long term, the critical threat to right whales is their low and inconsistent birth rate, which could be linked to pollutants or to poor nutrition. The latter, in turn, may be caused by shifts in food supplies linked to changing oceanographic or climate conditions. The OLI Initiative includes research to:

- analyze whale fecal samples to get previously unobtainable data on whale genetics, and hormone and contaminant levels
- conduct detailed studies on the effects of chemical pollutants and nutrition on whale health and reproduction
- develop new technology to monitor conditions in whale feeding grounds
- learn why whale feeding grounds exist where they do and how they change with changing oceanographic and climatic conditions
- deploy rapid-response expeditions to explore whale feeding and diving behavior.

Tracking the population

To monitor the whale population more effectively, the OLI Right Whale Initiative includes:

- expeditions to recover and analyze whale bones left behind from 16th-century whaling to help determine the North Atlantic right whale population's pre-whaling size and genetic diversity
- new aerial surveys using high-definition camera systems that provide more detailed information on whale conditions and behaviors
- development of comprehensive databases to share right whale information more widely and quickly
- modeling studies to target critical factors threatening the population and more effective conservation strategies.

Time is running short for the North Atlantic right whale. Now is the time for scientists and supporters to work together to keep this magnificent mammal swimming off our shores.

The Secret Lives of Fish

Scientists learn to read the 'diary' recorded in the ear bones of fish

By Simon Thorrold, Associate Scientist
Biology Department, and
Anne Cohen, Research Associate
Geology & Geophysics Department
Woods Hole Oceanographic Institution

The ocean's once-abundant fisheries—a resource that helps feed the world and drives multi-billion-dollar economies—are rapidly being depleted. Seventy percent of the ocean's fish are being fished at or above catch limits that would sustain the fish stocks, according to a recent report by the National Research Council.

This dismal situation has led to calls for Marine Protected Areas (MPAs)—areas completely closed to fishing—as a means to protect both fish stocks and the environments they inhabit. Instead of trying to manage single species in isolation, the idea is to manage and preserve whole ecosystems. (See "Do Marine Protected Areas Really Work?" page 42.)

But which areas should we designate to protect fish stocks most effectively? To make these decisions, we need to know details about fish life cycles, movements, and migrations. Unfortunately, large gaps remain in our knowledge about the secret lives of fish.

Following fish in a vast ocean

On land, the task is much easier. To learn about movements of terrestrial animals, researchers usually conduct tag-recapture studies. They place tags on a number of animals, release them, and

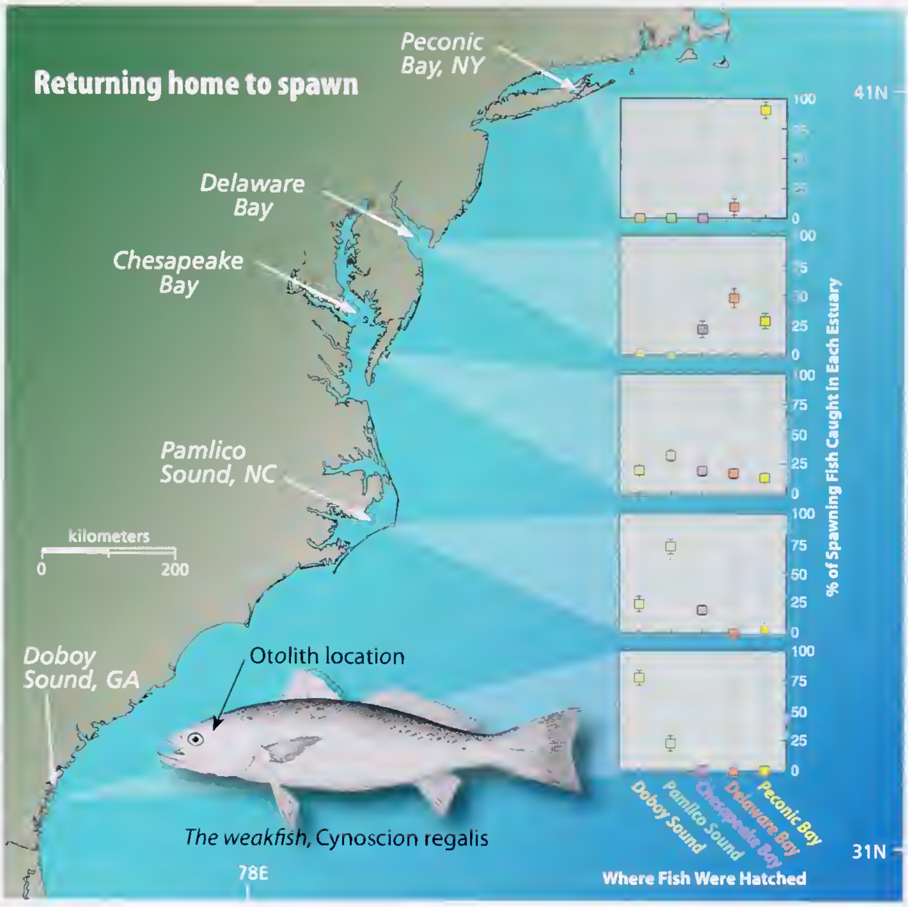
Tom Kleindinst, WHOI Graphic Services

LAYERED LOOK—Simon Thorrold examines a magnified otolith (ear bone) of a weakfish. Dark and light lines are alternating layers of calcium carbonate and protein, secreted as layers, which can be detected as annual, or even daily, rings.

then keep track of where the tagged animals were released and where they were found at later times.

Such studies are difficult in marine environments. Larval fish, generally only 5 millimeters or less in size, are too small to tag. In addition, fish typically lay millions of eggs, of which 99.9% do not survive. Even if we could tag hatchlings, we would lose nearly all of our study subjects before they reached adulthood.

Consequently, fisheries scientists have no way to know where an adult haddock caught on Georges Bank was spawned, or the location of the nursery area where it spent its adolescence, or the likelihood that it would return as an adult to spawn in the same place. Yet, this is exactly the information about fish species that we need to select and design MPAs that will effectively conserve and replenish fish populations.



Scientists analyzed the chemical compositions of otoliths of spawning weakfish caught in five estuaries to determine the estuary where they hatched. The small graphs show the percentage of fish caught in each estuary and where they hatched. The results indicate that most fish returned to their natal estuary to spawn.

Their ears can tell tales

Our recent research points to a promising new way to reveal where and how fish live their lives. Within all fish are ear bones, called otoliths. They grow throughout each fish's life, adding annual rings, similar to the growth rings in trees. For more than a century, biologists have used otoliths to estimate fish's ages.

But otoliths may be able to tell us far more. Otoliths consist of alternating layers of calcium carbonate and protein, which are deposited in daily increments. Through a complicated process, the chemical composition of the calcium carbonate is influenced by the chemical composition and temperature of the water the fish inhabit. If a fish swims into waters with different chemical or physical properties, those differences will be recorded chemically in its otoliths.

In other words, the otoliths can tell us where the fish has been. And because otolith layers remain unchanged once they are deposited, they can tell us when the fish was there. In addition, in some fish species, the width of each daily growth increment in the otoliths can be correlated with the growth rate of the fish.

Keys to unlock the 'black box'

In many ways, otoliths can be thought of as the fish-equivalent of an airplane's flight data recorder. They are continually logging information about the growth and health of the fish and about the water it swims in. Since otoliths begin to grow just before or after hatching, the entire life history of individual fish is available to be read, albeit in code.

Unfortunately, accessing information from flight data recorders is simpler than retrieving it from the otolith "black box." Scientists can determine the chemical composition of samples taken from many calcium structures, such as coral skeletons or clamshells, by using a mass spectrometer. This instrument sorts individual elements within a sample according to their mass and measures the amounts of each.

But such analyses generally require fairly large amounts of material. Each day, fish deposit only an extremely thin layer of otolith—about 10 micrometers (0.0004 inches) in width. Most mass spectrometers cannot be used on such small sampling scales.

To determine the chemical composition of daily growth increments, scientists need to analyze thin (5- to 10-micrometer) sections of otoliths. To analyze these thin sections, they require special types of mass spectrometers that use microbeams of ions or laser probes.

Scientists are fortunate to have access to such state-of-the-art mass spectrom-

Tom Kleindinst, WHOI Graphic Services

Tiny otoliths (like this one from a snapper fish) provide large amounts of information about the life histories of fish.

eters, including the Northeast National Ion Microprobe Facility (NNIMF) and the Plasma Induced Multi-Collector Mass Spectrometer (PIMMS) facility, located at Woods Hole Oceanographic Institution. These provide precise measurements of minute quantities of trace elements and isotopes in thin sections of the otoliths. These measurements give us the ability to discern small differences in chemical composition that occur within time periods as short as days.

Cracking the chemical code

Once collected, the data are still difficult to interpret. When otoliths form, they are surrounded by the fish's internal fluids. These fluids are separated from the ambient water on the other side of the fish's scales. So the possibility has existed that otolith chemistry has no relationship to the chemistry of the ambient seawater outside the fish.

Our research shows evidence, however, that chemistry of the water the fish swims in does indeed influence the chemical composition of its otoliths. We demonstrated in the laboratory that for at least two elements, barium and strontium, there is a direct, linear relationship between concentrations of these elements in the ambient water and in the otoliths. This may hold true for other elements, too.

If the properties of ambient water do influence the chemical composition of the otoliths on a daily basis, can we use the variations in composition as natural records of a fish's hatching location and subsequent travels?

A treasure trove of fish data

We have recently shown that we can do so with a natural, wild population of weakfish (*Cynoscion regalis*). Currently, these fish are managed as if they are a single population along the whole U.S. East Coast. That is because weakfish living from Florida to Maine show no genetic differences. Weakfish are an important commercial and recreational species that hatch in estuaries, spend their adulthood near the bottom in coastal waters, and return to estuaries to spawn.

Juvenile weakfish, however, hatch in each of five different East Coast estuaries. They are Doboy Sound, Ga.; Pamlico Sound, N.C., Chesapeake Bay, Va.; Delaware Bay, Del.; and Peconic Bay, near the end of Long Island, N.Y.

We have found that otoliths of fish born in each of the five natal estuaries had different, unique isotope and element compositions, or "signatures." All their lives, these fish had carried a natural tag, encoding the location where they were hatched.

We then analyzed otolith cores (the first portions deposited by hatchlings) from adult fish in those estuaries, and we found that most adult fish were returning to their birthplaces to reproduce —not randomly to any of the five possible natal estuaries. Knowing this means that protecting just one or two natal estuaries might not be sufficient to maintain the fish stocks.

We now believe that fish otoliths are a rich source of demographic information for fisheries scientists all over the world. At least one million otoliths are sectioned in laboratories every year, primarily to determine the fish's ages. Now we know that annual and daily growth increments in otoliths contain significantly more information about the lives of fish than simply their age. Chemical signatures in the otoliths offer the potential to reveal where and when a fish traveled throughout its life.

The development of techniques for decoding this otolith archive gives us a powerful new tool to help manage fisheries resources. If we know where fish hatch and travel, and where the spawning adults originate, fisheries managers will be better able to choose the most effective locations to site MPAs and to restrict fishing—to protect the world's diminishing fish resources.

Jean Pigozzi

Simon Thorrold (right) received a B.S. from the University of Auckland and Ph.D. from James Cook University, North Queensland, Australia. From his birthplace in New Zealand, he has traveled far across the Pacific to the Caribbean Marine Research Center, Old Dominion University in Virginia, and to WHOI in 2001. Using geochemical markers, he traces dispersal, migration, and population dynamics of marine invertebrates and fish, including clownfish. He has developed methods of correlating the chemical composition of fish ear bones with the water fish live in and travel through. With much of his work in the South Pacific and Caribbean, Thorrold has been on many cruises, logging 1,000 hours of scuba diving and 800 hours in tropical environs.

Phil Lobel

Growing up in coastal South Africa, Anne Cohen never knew snow, and spent time on the beach collecting shells. For her Ph.D. at the University of Cape Town, she studied shell composition and structure, using them to reconstruct the paleoceanography of west Africa's Benguela Current. She arrived in Woods Hole in winter, 1994, in T-shirt, jeans, and sandals, with a 6-foot coral core. At WHOI, she studied how corals record climate, and learned to scuba dive with sharks on a Pacific reef. She has added sponges, deep corals, and fish otoliths to her list of interesting structures to study. Cohen and her husband, also a scientist, grow crystals and run after their young daughter on weekends.

In tiny ear bones, the life story of a giant bluefin tuna

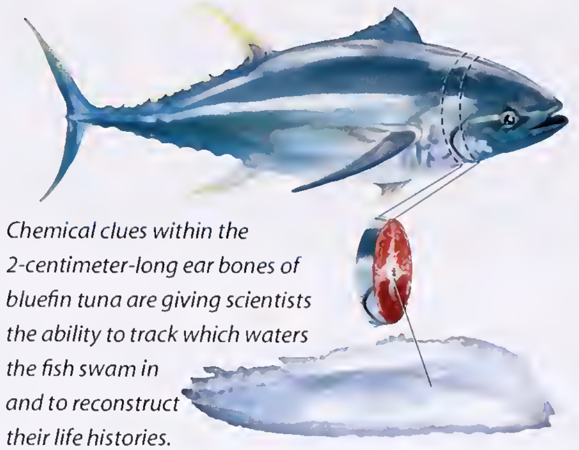
The Atlantic bluefin tuna, *Thunnus thynnus*, is one of the fastest, most powerful and most beautiful of fish. It is also the most expensive. Highly prized by sushi connoisseurs, a single giant fish of 1,400 pounds may sell for $40,000.

The tuna's high price has led the fishery to the brink of collapse. In 1981, in response to declining numbers of tuna, the International Commission for Conservation of Atlantic Tunas (ICCAT) introduced a strict management policy for Atlantic bluefin that rapidly developed into one of the most controversial and politically charged issues in fisheries management.

The policy controversy, familiar to both commercial and recreational New England fishermen, centers on the assumption that there are two discrete and independent North Atlantic populations. The two populations are arbitrarily divided into eastern and western territories at the 45°W meridian. Each presumed stock is subject to different management restrictions, the most striking of which is the imposition of a strict, near-zero harvest quota for the western stock and the absence of country-specific quotas for the eastern stock.

There is considerable debate concerning the appropriateness of the two-stock division because evidence is lacking to support its two key assumptions. The first is that eastern and western tuna populations reproduce separately in separate spawning grounds, with western fish spawning in the Gulf of Mexico and eastern fish in the Mediterranean. The second is that the tuna populations do not migrate across the Atlantic and intermingle.

A large research effort is currently underway to test these assumptions by tracking the movements of individual fish across the North Atlantic and studying their spawning behavior. Much of this effort—led by Barbara Block of Stanford University and Molly Lutcavage of the New England Aquarium—has involved the use of sophisticated pop-up satellite tags.



Chemical clues within the 2-centimeter-long ear bones of bluefin tuna are giving scientists the ability to track which waters the fish swam in and to reconstruct their life histories.

E. Paul Oberlander, WHOI Graphic Services

Pop-up satellite tags presently have limited lifespans, ranging perhaps from months to years. At Woods Hole Oceanographic Institution, we are investigating the feasibility of using chemical signatures in the otoliths, or ear bones, of giant fish to obtain information about trans-Atlantic migrations, stock mixing, and spawning habitats. The entire, detailed life history, from birth to death, of a giant 30-year-old bluefin is contained within a single otolith less than one inch long.

Our approach is based on the premise that differences in water chemistry and temperature experienced by fish during their travels will be recorded as distinct and predictable changes in the trace elements of aragonite, the mineral that makes up the otolith. This approach differs from most previous otolith studies in our use of microbeam technology to track chemical changes at weekly to daily resolution within a single ear bone.

Using the micron-scale sampling capabilities of the Cameca 3f ion microprobe and techniques developed to study coral skeletons, we have been able to analyze the chemical composition of the primordium, a region of otolith just 20 microns in diameter. The primordium forms when the fish is still in the larval stage, and its chemical composition contains a record of where the fish was born.

Our initial results are promising and show that we may be able to use chemical signatures in the primordium to distinguish different populations of bluefin tuna—in their first years of life when the primordium is being formed. With conventional bulk sample analyses, we are not able to distinguish between different stages (i.e. larval, juvenile, adult) of otolith formation. By contrast, our new approach gives us the ability to reconstruct the life history of the fish from birth to death.

Because we can obtain a daily record of the tuna's travels, rather than average, we may be able to tell when, during the tuna's long life, it swam in which waters. We can potentially discern whether the tuna was born in the west and migrated east, or was born in the east and migrated west, instead of knowing only that it was in both areas sometime during its life. This will improve our ability to manage populations of this magnificent fish.

—Anne Cohen and Graham Layne
(Layne is a WHOI research specialist.)

Enric Ballesteros

Tracking Fish to Save Them

The Reef Fish Connectivity and Conservation Initiative

By Simon Thorrold, Associate Scientist
Biology Department,
Woods Hole Oceanographic Institution

For decades, the Nassau grouper (*Epinephelus striatus*) was one of the most sought-after fish species in the Caribbean and Gulf of Mexico, from the Bahamas to Central America. These large, delicious fish live among coral reefs and have a breeding behavior that makes them especially vulnerable. They come together in aggregations of thousands to spawn at specific times and places, making them easy to catch—and to overfish.

Nassau grouper populations have been severely depleted by humans throughout most of their range. The environmental and economic ramifications are alarming, and regional governments are responding by restricting or prohibiting fishing for them.

But several large spawning aggregations of this species still exist in the western part of its range near Belize, in the Meso-America Barrier Reef System. These aggregations may provide our last opportunity to learn if and how fish populations are connected among isolated reef sites. This information will be critical if we are to save the Nassau grouper populations from local extinction, as has already occurred on some Caribbean islands.

No fishing allowed

Marine ecosystems in all the world's oceans are under considerable and increasing stress from human activities, precipitating urgent calls for new ways to counter the impacts of people. Resource managers are increasingly using Marine Protected Areas (MPAs)—areas completely closed to fishing—as a means to maintain fisheries and biodiversity.

But scientists, fishermen, environmentalists, and governments continue to debate the effectiveness of MPAs. (See "Do Marine Protected Areas Really Work?" page 42, and "Can We Catch More Fish and Still Preserve the Stock?" page 45.) Monitoring mobile animals under water over long distances and times is difficult, if not impossible, so scientists use mathematical models of population growth to predict the effectiveness of fishing closures. Yet we don't know enough about one important component of such a model—how fish move in and out of MPAs. To predict how well MPAs work, we will need models that accurately describe the movement of individuals between geographically separated sites—what is termed population connectivity.

A critical part of estimating connectivity among geographically separated groups of fish is tracking the dispersal of larval fish. Until recently, there has been no way to tell if adult fish living in one reef habitat were spawned in a different location. We did not have the means to determine where fish were spawned, because most fish larvae are too small to be tagged by conventional means.

Revolutionary tagging technology

But now, scientists at Woods Hole Oceanographic Institution have achieved a breakthrough that is poised to revolutionize the study of larval dispersal in marine fish. We have demonstrated that it is possible to introduce a unique chemical tag into the ear bones (otoliths) of fish embryos by injecting the female before she spawns with a nontoxic isotope.

The isotope is a variant of the elements barium or strontium, which would normally be incorporated in small amounts (along with calcium) into the fish's ear bone as it grows. But the isotope has a slightly different mass than the common form of the element.

The otolith grows as the fish grows, with layers that are laid down like tree rings during the fish's life. All the material in the otolith remains where it was originally deposited; it is not continually turned over, as happens in other bones. An isotope with different mass "built into" the ear bone at the start of life will always be there, in minute amounts, at the center, or earliest, part of the otolith. This tag remains in the otolith throughout the fish's life, wherever it travels.

Ear bones tell the tale

When the fish is caught, we can remove the otolith, and use a mass spectrometer equipped with a laser system to detect the tag. (See "The Secret Lives of Fish," page 36.) A narrow laser beam from the instrument ablates, or vaporizes, selected parts of the otolith (in this case, the first-formed area, or core), and the isotopic composition of the vaporized material is then automatically analyzed to reveal whether the isotopic tag is present. Fish can be identified as the offspring of a tagged parent if the otolith core contains significantly more of the rare isotope injected into the parent, as compared with control samples with natural isotopic compositions.

Beginning in 2005, we will employ this new technique on large, long-lived species that aggregate to spawn at specific times and places and produce planktonic eggs, particularly the Nassau grouper, in coral reefs off Belize. It will give us the ability to learn for the first time whether Nassau groupers—tagged at spawning—disperse to other parts of their range during their larval lives. We will also be able to determine the extent to which fish hatched in an MPA return to their natal location, are dispersed from the MPA to areas open to fishing, or are recruited to other protected habitats.

A conservation partnership

Applying this innovative technology, the WHOI Ocean Life Institute (OLI) is launching the Reef Fish Connectivity and Conservation Initiative. The project is funded in large part by the Oak Foundation, a private philanthropy whose priorities include conservation of the marine environment, and by OLI. The initiative will partner WHOI with a multinational large-scale study of coral reef fish and ecosystems called the Targeted Coral Reef Research Project, funded by the Global Environmental Facility (GEF) and implemented by the World Bank. GEF is an independent organization that receives contributions from donor countries and funds projects that benefit and promote sustainable ecosystems in developing countries. The World Bank helps GEF implement projects in theme areas of critical global interest, including biodiversity.

Depletion of fish stocks in the tropical coastal regions and coral reefs of the world is a large and growing problem. In many places in the Caribbean, the loss of 80 to 90 percent of grouper populations to overfishing has meant significant losses to fishermen and local economies and severe degradation to ecosystems. Scientists, conservation groups, private foundations, and governments, along with financial and economic organizations such as the World Bank are concerned—and beginning to work together. With such support, new scientific approaches such as otolith tagging may provide information that resource managers and policy-makers can use to design and implement Marine Protected Areas that will protect marine populations vulnerable to human exploitation, including the Nassau grouper.

DWINDLING FISH POPULATIONS—Fishermen have long sought Nassau groupers, which live among coral reefs in the Caribbean Sea, from Central America to the Bahamas and Bermuda. In recent decades, 80 to 90 percent of grouper populations have been lost to overfishing.

Do Marine Protected Areas Really Work?

Georges Bank experiment provides clues to longstanding questions about closing areas to fishing

By Michael J. Fogarty, Adj. Associate Scientist, Woods Hole Oceanographic Institution and NOAA Fisheries Service, Northeast Fisheries Science Center and Steven A. Murawski, Director, Office of Science and Technology, NOAA Fisheries Service, Silver Spring, MD

Closing parts of the ocean to fishing to preserve fish stocks holds great intuitive appeal. Similar resource management tools have been used as far back as the Middle Ages, when European kings and princes controlled access to forests and streams, and the fish and wildlife in them. In Hawaii, chiefs established and maintained networks of no-fishing "kapu" zones, with violations punishable by death.

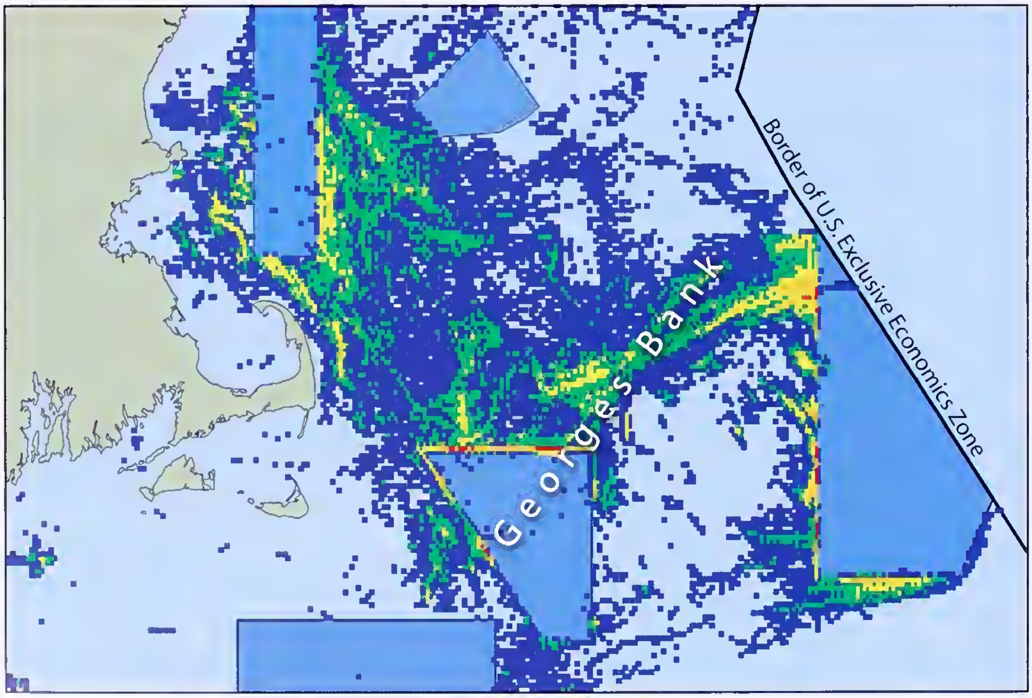
Today, Marine Protected Areas, or MPAs—areas of the ocean temporarily or permanently closed to harvesting—are being proposed to restrict not only fishing, but also mineral and hydrocarbon extraction, and other activities. Some advocates of MPAs suggest that at least 20 percent of the coastal and open ocean should be set aside and permanently zoned to protect ecosystems, sustain fish stocks, and reduce conflicts between users of the oceans.

But the key question remains: Do MPAs really work? It is the modern incarnation of a longstanding question: How can we best ensure sustainable fisheries?

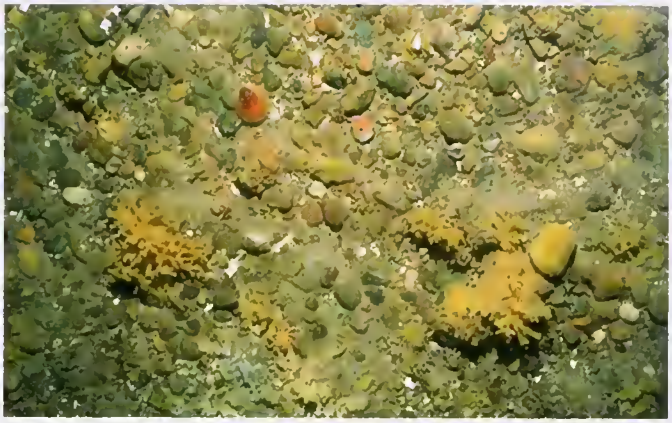
A Victorian model

In the 19th century, scientists vigorously debated the effects of fishing on fish populations and ecosystems. A majority of scientists accepted the paradigm that the oceans were unlimited. Thomas Henry Huxley, a preeminent Victorian naturalist, famously stated in 1884 that: "... *the cod fishery, the herring fishery, the pilchard fishery, the mackerel fishery, and probably all the great sea-fisheries, are inexhaustible; that is to say that nothing we do seriously affects the number of fish ... given our present mode of fishing. And any attempt to regulate these fisheries consequently ... seems to be useless.*"

The debate culminated in one of the first documented experiments to determine the effects of fishing. In 1886, one bay in Scotland remained open while another was closed to fishing for 10 years. The focus of the experiment was plaice, a valuable commercial fish. Over the decade, plaice in the closed bay increased significantly compared to plaice in the open



FISHING AT THE BORDERS—Georges Bank and surrounding areas with historically abundant fisheries have seen fish stock depletion and fishery collapses. To speed stock recovery, Marine Protected Areas (MPAs) closed to fishing have been established (blue polygons). Dots show fishing effort in 2003, based on satellite tracking of vessels moving at less than 3.5 knots and assumed to be towing fishing gear. Warmer colors (green to red) denote more intense activity. The highest intensity of fishing occurred right at MPA borders, indicating that fishers expected greater abundance there.



Dann Blackwood, courtesy of Dr Page Valentine, USGS

THE DIFFERENCE A DREDGE MAKES—Dragging fishing gear over the oceam bottom causes severe damage to seafloor habitats and organisms. At left, a normal seafloor community on Georges Bank; at right, a similar area after dredges have been used to harvest scallops.

bay. It was an early, instructive demonstration that fishing does have impacts on fish populations, and that regulation is effective for conservation.

Some ABCs of MPAs

Since then, seasonal and longer-term closures have been an important fishery management tool, and they have protected spawning fish and nursery areas, preserved vulnerable habitats, and reduced fishing pressure.

But by themselves, MPAs cannot attain all of today's fishery management objectives. And they can create unintended consequences. Preventing harvesting in some areas, for example, inevitably results in people fishing in other, perhaps more vulnerable, locations.

MPAs have now been established throughout the world ocean, from the tropics to the poles. Most are relatively small. Many are neither adequately enforced nor monitored to determine their effectiveness.

Of those that have been scientifically monitored, many are in tropical and subtropical areas. Fish in these regions live most of their lives in specific habitats, such as reef structures, and don't stray from them. Their fidelity to a small territory is an important part of the potential success of their marine reserve. Populations do increase in such reserves, and some studies suggest a spillover effect from the reserve that augments fisheries nearby.

By contrast, in temperate, boreal, and subarctic systems—where most of the major world fisheries reside—many fish populations are wide-ranging and often exhibit extensive seasonal migrations. Can a reserve by itself be a successful fishery management tool for these fish?

The Georges Bank 'experiment'

In 1994, federal regulations established a number of year-round fishery closures on Georges Bank and adjacent areas. This shallow bank has sustained fisheries of legendary abundance for hundreds of years until the mid-20th century, when the heavily fished stocks declined steeply.

The year-round closures evolved from seasonal closures established in the 1970s by the International Commission for Northwest Atlantic Fisheries to protect spawning groundfish, particularly haddock. The current year-round closed areas—on Georges Bank and two nearby areas—encompass more than 20,000 square kilometers. It is one of the largest systems of closed fishing areas now in effect. In addition, a mosaic of seasonally closed areas in the Gulf of Maine eliminates fishing in virtually all parts of the gulf at one time or another.

At the same time, the National Oceanic and Atmospheric Administration also restricted the number days at sea that fishermen could fish. Fishing by trawlers declined by more than 40 percent over the next five years, although fishing with static gear, such as lobster traps, gillnets and longlines, and limited scallop harvesting, is still allowed in the closed areas.

These closures have given us a unique opportunity to examine a marine protected area in a temperate system under a "macroscope"—to investigate how marine ecosystems are structured and how they function and recover. The long history of research on Georges Bank adds a foundation of scientific knowledge that makes the Georges Bank MPA ideal for testing the effects of year-round fishery closures and adds essential observations to test models. (See "Can We Catch More Fish and Still Preserve the Stocks?" page 45.)

In the aftermath of closures

We have several ways to assess the Georges Bank and nearby MPAs. We have monitored fish and shellfish populations to get detailed comparisons of abundances and sizes of animals within and outside the closures, both before and after the establishment of the MPAs. Together with information from the commercial fishery and from scientific studies, the results let us see the impacts of the closed areas on seafloor organisms and communities, on the physical structure of the habitat, and on population levels of fish and shellfish species.

It is not easy to separate the effects of the closed areas on Georges Bank from other changes, such as fishing-days reductions implemented at the same time. How-

ever, our studies show that the closures have played an important role in the overall increase in abundance of these stocks:

- The biomass (total population weight) of a number of commercially important fish species on Georges Bank has sharply increased, due to both an increase in the average size of individuals and, for some species, an increase in the number of young surviving to harvestable size.
- Some non-commercial species, such as longhorn sculpin, increased in biomass.
- By 2001, haddock populations rebounded dramatically with a fivefold increase.
- Yellowtail flounder populations have increased by more than 800 percent since the establishment of year-round closures.
- Cod biomass increased by about 50 percent by 2001.
- Scallop biomass increased 14-fold by 2001, an extra benefit of the establishment of closed areas primarily intended to protect groundfish.

Eggs and larvae to seed the seas

Despite increases in biomass, MPAs benefit a fishery only if fish eggs and larvae are exported from closed areas to replenish open, harvested areas, and/or if some harvestable-size stock "spills over," moving from closed to open areas to be caught. But if fish at any age leave closed areas at high rates, it will prevent a buildup within the reserve and cancel out any positive effects from the MPA.

Estimating the export of eggs and larvae is extremely difficult. But we can use the location of spawning aggregations and hydrodynamic models to estimate the magnitudes and directions of eggs and larvae dispersal.

On Georges Bank, a key factor in larval dispersal is a well-established clockwise circulation pattern, or gyre, resulting from factors including local tidal forces and seafloor topography. The gyre creates a conduit that may allow eggs and larvae to self-seed closed areas, cross-seed other closed areas, and transport larvae to open areas. Our analyses for scallop larvae indicate that the closed areas on Georges Bank can be self-sustaining and also contribute to recruitment into other areas.

Spillover and trawling impacts

Our initial findings on spillover amounts show that the MPAs have benefited fisheries for some species, but not all. Using information from the commercial fishing fleet, we found significant spillover for haddock and for yellowtail and winter flounders near some closed areas, but no spillover for other commercially important species.

But the commercial fleet clearly expects spillover from MPAs. Satellite tracking shows that large trawlers concentrate fishing efforts on the borders of the closed areas, poised to pounce on any fish that stray over the boundaries.

Scientists from the Northeast Fisheries Science Center, University of Rhode Island, and the U.S. Geological Survey have documented the impacts of mobile fishing gear, such as bottom trawls and dredges, on bottom-living (benthic) communities of organisms. Comparing detailed photographic images of sites inside and outside the Georges Bank closed areas, they have measured the damage done to the seafloor.

The difference is striking: We can see the recovery of benthic organisms inside the closed areas and watch community structure re-emerge as a result of the MPA.

Benefits beyond fisheries

The large-scale management experiment on Georges Bank indicates that a combination of MPAs and other management measures, such as reduced fishing efforts, can allow some species to recover from overexploitation. And beyond protecting fisheries, MPAs potentially offer other benefits. They can:

- help preserve marine ecosystems and biodiversity of non-targeted fishery species by curtailing trawling damage or inadvertent catch
- promote non-extractive uses of marine areas, like eco-tourism
- establish undisturbed locations for scientific studies that can further improve resource management and conservation.

To make the best use of MPAs, though, we have to clearly specify our objectives. We then must evaluate the effectiveness and the social and economic impacts of MPAs and compare the utility of MPAs with other possible management tools to see if they are the best option for the situation. The Georges Bank experience has proven very instructive in how to implement and evaluate marine protected areas in temperate seas—and the experiment is still going strong.

Anne Richards

Michael Fogarty started life far from the ocean, in Fairbanks, Alaska. His parents, New England natives, eventually returned to Rhode Island, where he became fascinated with sea life and embarked on a career in marine biology. He received a doctorate from the University of Rhode Island and came to the Northeast Fisheries Science Center in 1980, where he studies changes in marine ecosystems in response to fishing. He has served on numerous national and international panels and committees, including the Scientific Steering Committee of the U.S. GLOBEC program, which he chaired from 1997 to 2002, and the Global Ocean Observation System (GOOS) Steering Committee. When not keeping the world safe for fish, he serves as a full-time chauffeur for his children, ages 9 and 12, who lead very busy lives.

NEFSC

Steven Murawski spent his formative years in Kansas and Texas, before moving to New England as a teen. Interested in fisheries and the ocean since he was a lad, he obtained degrees at the University of Massachusetts-Amherst. Since coming to the Northeast Fisheries Science Center, he has been involved with determining how many fish of various species are in the ocean, and how many should be caught—the process of stock assessment. Murawski will soon be the Director of the National Marine Fisheries Service's Office of Science and Technology. He lives in Massachusetts with his wife, daughters, and a golden retriever.

Can We Catch More Fish and Still Preserve the Stock?

Mathematical analyses offer new insights into age-old controversies on fishing restrictions

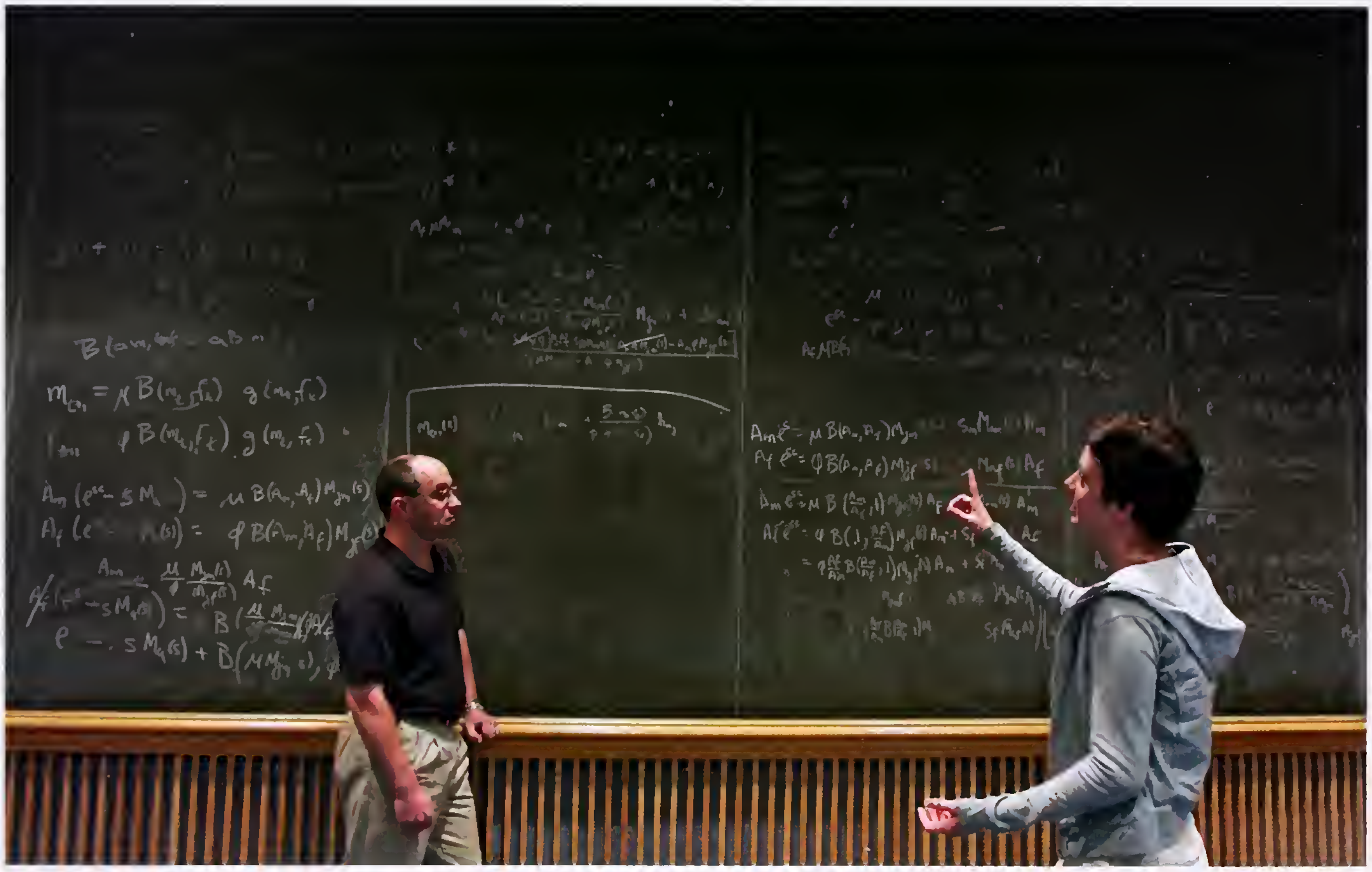
Michael Neubert, Associate Scientist
Biology Department
Woods Hole Oceanographic Institution

Near the town of Webster in southern Massachusetts there is a small lake with a long name: Lake Chargoggagogg-manchauggagoggchaubunagungamaugg. The correct translation, from the original Native American language, refers to Englishmen fishing at a certain place, near a boundary. But a humorous translation in a 1916 newspaper article, now accepted the world over, is: "You fish on your side; I fish on my side; nobody fishes in the middle."

People have always fished. But the history of fishing is also the history of overfishing. For hundreds of years, the establishment and enforcement of fishery management policies have generated controversy, as competing authorities have searched for a way to balance competing goals—to catch as many fish as possible while conserving the resource. To resolve this dilemma, we have applied mathematics—and we are finding that the ancient solution may still prove effective in modern times.

Conflicting policies and goals

In May 2000, President Bill Clinton issued Executive Order 13158, expanding a 20-year-old fisheries management law, the Magnuson-Stevens Act. The



Tom Kleindinst, WHOI Graphic Services

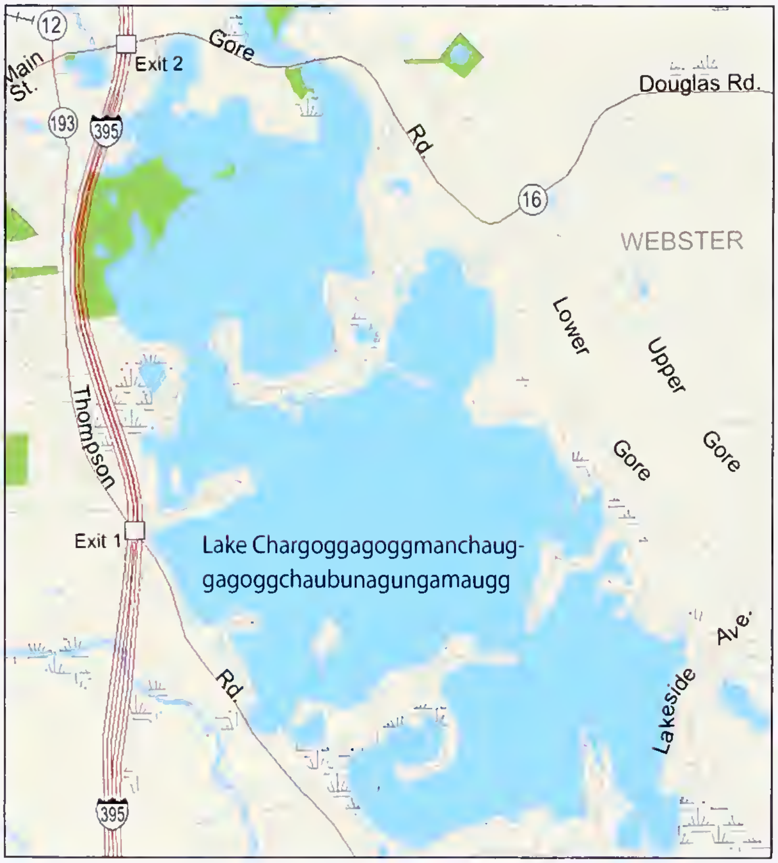
SEARCHING FOR SOLUTIONS—Michael Neubert (left), WHOI mathematical ecologist and biologist, discusses equations with Alison Shaw, an undergraduate student in the WHOI Summer Student Fellowship Program. Mathematical models can yield information about population ecology that complements traditional monitoring methods.

order requires the National Oceanic and Atmospheric Administration (NOAA) and other federal agencies to establish new Marine Protected Areas (MPAs) and to expand the protection of existing MPAs. An MPA is defined as "any area of the marine environment that has been reserved by federal, state, territorial, tribal or local laws or regulations to provide lasting protection for part or all of the natural and cultural resources therein." MPA examples include National Marine Sanctuaries, Federal Threatened/Endangered Critical Habitat and Species Protected Area sites, and National Estuarine Research Reserve system sites.

The language of this order clearly emphasizes conservation. But NOAA has another mandate: to manage fisheries, "while achieving, on a continuing basis, the optimum yield from each fishery for the United States fishing industry." Does the MPA approach work for the dual purpose of increasing conservation and maximizing yield?

The growing weight of scientific opinion is that MPAs do protect endangered species and conserve essential habitats. (See "Do Marine Protected Areas Really Work? page 42.) In fact, in a surprising show of unanimity, more than160 marine scientists signed a statement documenting their consensus that marine reserves have ecological benefits (http://www.nceas.ucsb.edu/Consensus/consensus.pdf). Inside such reserves, fish population sizes, biomasses, organism sizes, and biological diversity are all typically higher than they are in ecologically similar but unprotected areas. "No-take marine reserves"—a type of MPA within which fishing is prohibited—seem to be particularly effective.

But what effects will expanding marine reserves have on the fisheries? Many people, and not just fishermen, believe it is impossible to obtain the maximum yield from a fishery while simultaneously setting aside areas as marine reserves. A congressional critic of marine reserves revealed some of the intensity of the debate during congressional hearings in 2002 when he said that "the marine reserve movement seeks to exclude the American public from a public resource without scientific justification for doing so…" (http://resourcescommittee.house.gov/archives/107cong/fisheries/2002may23/peterson.htm).



AHEAD OF THE TIMES—This lake in Webster, Mass., has a long name derived from the Native American Nipmuk language. The widely known (though incorrect) translation ("You fish on your side; I fish on my side; nobody fishes in the middle") may foretell how Marine Protected Areas can ensure the greatest fish abundance.

A web of interrelated factors

The essential questions are: Can NOAA simultaneously fulfill its conservation and fisheries management missions, and can they do so using marine reserves?

These are tough questions, because they are both complex and vague. Scientists prefer to try to answer simple, concrete questions. Therefore, when I began to think about MPAs, I changed those two questions into these three:

1. Is it possible to maximize the sustainable yield of a fishery using marine reserves?
2. If so, how big should they be?
3. Where should they be placed?

These questions intrigued me, and so I set about trying to answer them using mathematics. At face value, it may not seem like my three questions are mathematical questions at all. But like most scientific questions in ecology, they are—and here's why:

The questions all involve optimally balancing various rates of change to achieve some goal. In this case, the goal is maximization of yield. The rates are individual growth rates, population growth rates, harvesting rates, dispersal rates, disturbance rates, and when economics is brought into the picture, interest rates.

Many of these rates interact with each other in nonlinear ways. For example, as harvesting rates increase, population size tends to decrease. When that happens, fewer individual fish compete for food, individuals may grow faster, and as a result, reproduce sooner.

This web of interacting rates is quite complicated.

There is no way to distill the consequences of the interactions of all of those rates, let alone figure out how to balance them in an optimal way, without using a mathematical model, which is a set of equations describing how the properties of a system depend on and relate to each other.

Models describe the behavior of a system in mathematical language—that is, equations. Models are powerful because they let us identify and separate critical factors (variables) affecting a changing system. By refining the equations, we can come closer and closer to describing the real system—and being able to predict it.

Limiting fishing—or places to fish

Fisheries biologists have a long tradition of using mathematical models, so I was not surprised to find that people had already attempted to answer my first question. They used models ranging from simulations of very complicated computer models to "pencil and paper" manipulations of very simple models.

For the most part, these analyses compared two types of fishing strategies. The first strategy seeks to find an ideal arrangement of marine reserves that maximizes fish yield by varying the size and placement of one or several reserves. The second, more "traditional" strategy is to vary the level of fishing uniformly over an entire area to maximize the yield. The results of these analyses, with few exceptions, show that the best-distribution-of-marine-reserves strategy and the more traditional fishing-limit strategy both produce the same yields.

Both analyses have problems, however. Both strategies assume that a reserve protects an unchanging fraction of the fish—those in the fixed area of the reserve. But in reality, as fish populations grow, a varying fraction of the stock will disperse out of the reserve area, so the remaining fish are also a varying fraction of the total—and the analysis doesn't account for that variation. Only a so-called "spatially explicit" model, which takes the locations and movement of the fish into consideration, will account for the biophysical reality of fish dispersal.

Surprising initial results

I set out to construct and analyze a spatially explicit fishery model and use it to determine the fishing strategy that produces the maximum possible yield—without assuming ahead of time that either of the usual strategies would be best. I kept the model simple enough that I could analyze it mathematically (which meant that I kept it *very* simple). In my model, all fish are identical, they live in a one-dimensional habitat of finite length, they move in a random fashion, and if they happen to leave the habitat, they die. The only limit I placed upon fishing effort was that it could not exceed some preset maximum level.

I used techniques from a field of mathematics called "optimal control theory" to figure out the best fishing strategy. This is the same theory that engineers use to figure out the most efficient way to control the motion and stability of airplanes, rockets, and submarines—hence the name.

The results of my analysis were surprising. The fishing strategy that maximized yield always included at least one marine reserve, and fishing strategies that did not include reserves were all less than optimal. In other words, fishermen actually catch fewer fish when there are no areas closed to fishing.

The optimal number of reserves depended upon the length of the habitat. If the habitat was large, the best arrangement of fishing took on a very intricate geometric structure—with infinitely many reserves alternating with areas of maximum fishing effort. Of course, such a complex distribution of fishing effort could never actually be used in the real world. But in every case—for every habitat length—I was able to find a strategy using only a few reserves that came very close to producing the maximum yield.

Deeper into the complexities

Are MPAs the best way to maximize yield in real fisheries? Will fish and fisheries both thrive if you fish on your side, I fish on my side, and nobody fishes in the middle? My results suggest that this is true.

There are, however, many assumptions and simplifications in my model that are open to objections. Fisheries biologists might assert that it's essential to account for population size structure, uncertainty about the variables, and changing environmental properties. Conservation biologists might demand an optimization that includes what they term an "existence value"—a non-consumptive value assigned to the fish's existence, whether or not anyone ever sees, or catches, the fish or its descendants. Biological oceanographers might object to the fact that my model ignores species interactions, or to the use of a one-dimensional model, or to the way that I described the movement of fish, which disregards ocean currents. Economists might argue that the maximization of sustainable profit, rather than the maximization of yield, should be the management objective.

Including some of these modifications in the model could change my results; others might not. I am looking forward to exploring these issues further during my tenure as an Ocean Life Institute Fellow.

Michael Neubert graduated from Brown University with a bachelor's degree in applied mathematics and biology and has been interested in the intersection between these two fields ever since. After receiving a Ph.D. in applied mathematics from the University of Washington in 1994, he came to the Woods Hole Oceanographic Institution as a postdoctoral scholar, and is now an associate scientist in the Biology Department and Fellow of the Ocean Life Institute. Most of his research uses ecological models that include a spatial component. Using spatial models lets him address important questions in ecology and conservation biology, such as: What determines how fast a population spreads through a habitat into which it is newly introduced? How much habitat does a population require to persist? How should one design a system of preserves to protect an endangered species? When not running ecological models, Neubert is usually running to the nearest coffee shop.

Voyages into the Antarctic Winter

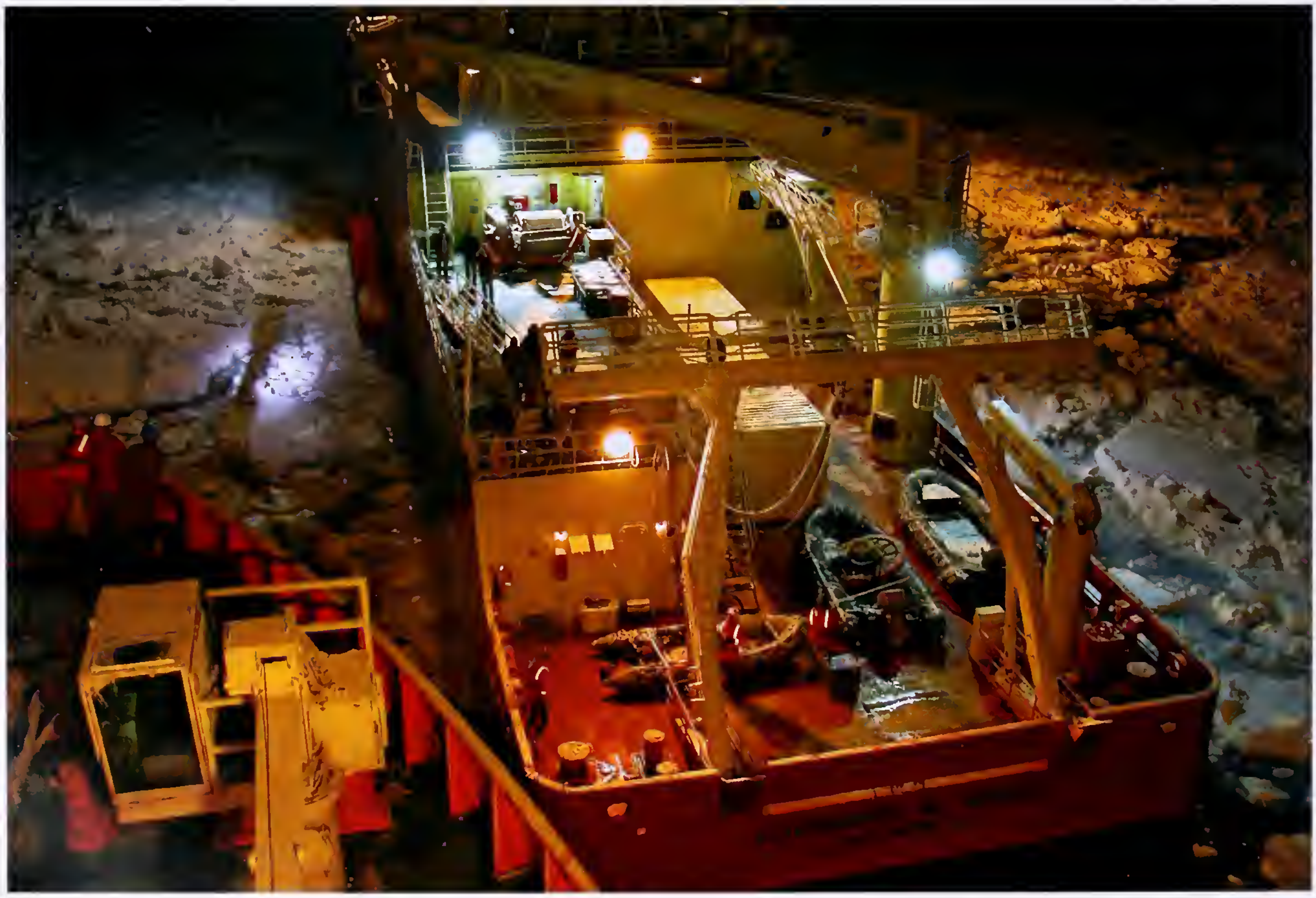
Pioneering cruises into the pack ice of the Southern Ocean reveal secrets of its fertile ecosystem

Peter H. Wiebe, Senior Scientist
Biology Department
Woods Hole Oceanographic Institution

At the extreme end of the Earth, Antarctica is a vast, rocky continent, mostly ice-covered and barren. Surrounding Antarctica, the Southern Ocean is equally vast, cold, and ice-covered. But unlike the land, it teems with life, ranging from microscopic plankton to top predators: whales, seals, penguins, fish, and sea birds.

The region's fecundity is fueled by 24-hour-a-day sunlight in summer, combined with ocean currents that bring essential nutrients. These provide the ingredients for rich blooms of microscopic marine plants and animals at the base of the food chain—phytoplankton and zooplankton—that are similar to those in many productive regions of the world's oceans.

But there is one big difference in the Antarctic ecosystem. The food moves swiftly to the very top of the chain through a crucial link: a shrimp-like crustacean called krill, which swarm in great pink oceanic patches that range from tens of square meters to tens of square kilometers. The krill connect the microscopic primary producers, which they eat, to the



Peter Wiebe, WHOI

ICY RENDEZVOUS—Two National Science Foundation research vessels, the Nathaniel B. Palmer *(left) and* Laurence M. Gould, *go bow to stern to exchange equipment, supplies, and personnel just west of Marguerite Bay during an unprecedented cruise into the winter pack ice off Antarctica.*

top predators, which eat them.

This unique and unusually short oceanic food chain is both strong and vulnerable. It efficiently supports large populations of big animals. But a small disruption in the chain could drastically affect the entire ecosystem.

Adding urgency are recent indications of changing conditions around Antarctica—particularly more frequent calving of massive icebergs from the continental ice shelf. To manage and protect this unique environment, we need a more thorough understanding of the intricacies of the ecosystem and the potential effects of climate change on it.

Krill are the glue that binds the Antarctic food web, and 20th-century expeditions learned a great deal about their life stages, distribution, and abundance—but only during the warmer, sunlit, ice-free periods of the year. How do adult and larval krill survive the frigid, sunless winter—when photosynthesis diminishes essentially to zero and much of the ocean is covered with pack ice—to become an abundant food source for large animals the next spring? To pull back the veil on this critical and previously shrouded part of the ecosystem, we undertook 11 cruises to the Southern Ocean, including four unprecedented voyages into the Antarctic winter ice pack.

Peter Wiebe, WHOI

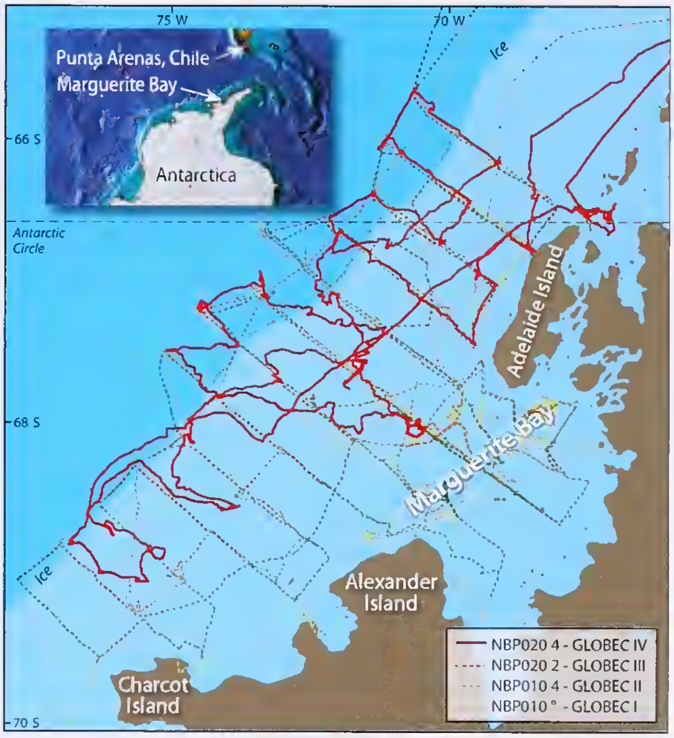
GOING FOR THE KRILL—BIOMAPER-II is lifted aboard the icebreaker Palmer, *which cleared a path in the ice to tow the vehicle behind it. BIOMAPER-II has an acoustic system to detect plankton and zooplankton, a video plankton recorder to take pictures of them, and sensors to measure water properties.*

Destination: Marguerite Bay

The cruises were part of the Global Ocean Ecosystem Dynamics Program (GLOBEC), a multiyear, multination, multidisciplinary series of investigations of several touchstone regions throughout the world's oceans where marine life and fisheries historically thrive. Marshalling scientists across several disciplines, GLOBEC sought to define and measure the many factors—oceanic currents, climatic conditions, seafloor topography, biological processes, and others—that converge to create and maintain productive ecosystems. GLOBEC also seeks to provide information on the vulnerability of ocean ecosystems to climate changes.

Fieldwork for the Southern Ocean GLOBEC program, conducted between 2001 and early 2003, focused on a broad and relatively deep (300 to 400 meters) continental shelf region off the western Antarctic Peninsula, due south of the tip of South America, from Adelaide Island to Charcot Island. In between lies Marguerite Bay, which supports a large, persistent stock of krill and large populations of top predators that depend on it for food. We suspect that this area may act as a reservoir for maintaining krill stocks hundreds of miles away in the Scotia Sea, as far as South Georgia Island.

Marguerite Bay is surrounded landward by high, snow-covered mountains and seaward by huge ice shelves. It is dotted by numerous small islands and persistently covered by sea ice in winter. Below the sea surface, the bay is gouged by a trough that cuts di-

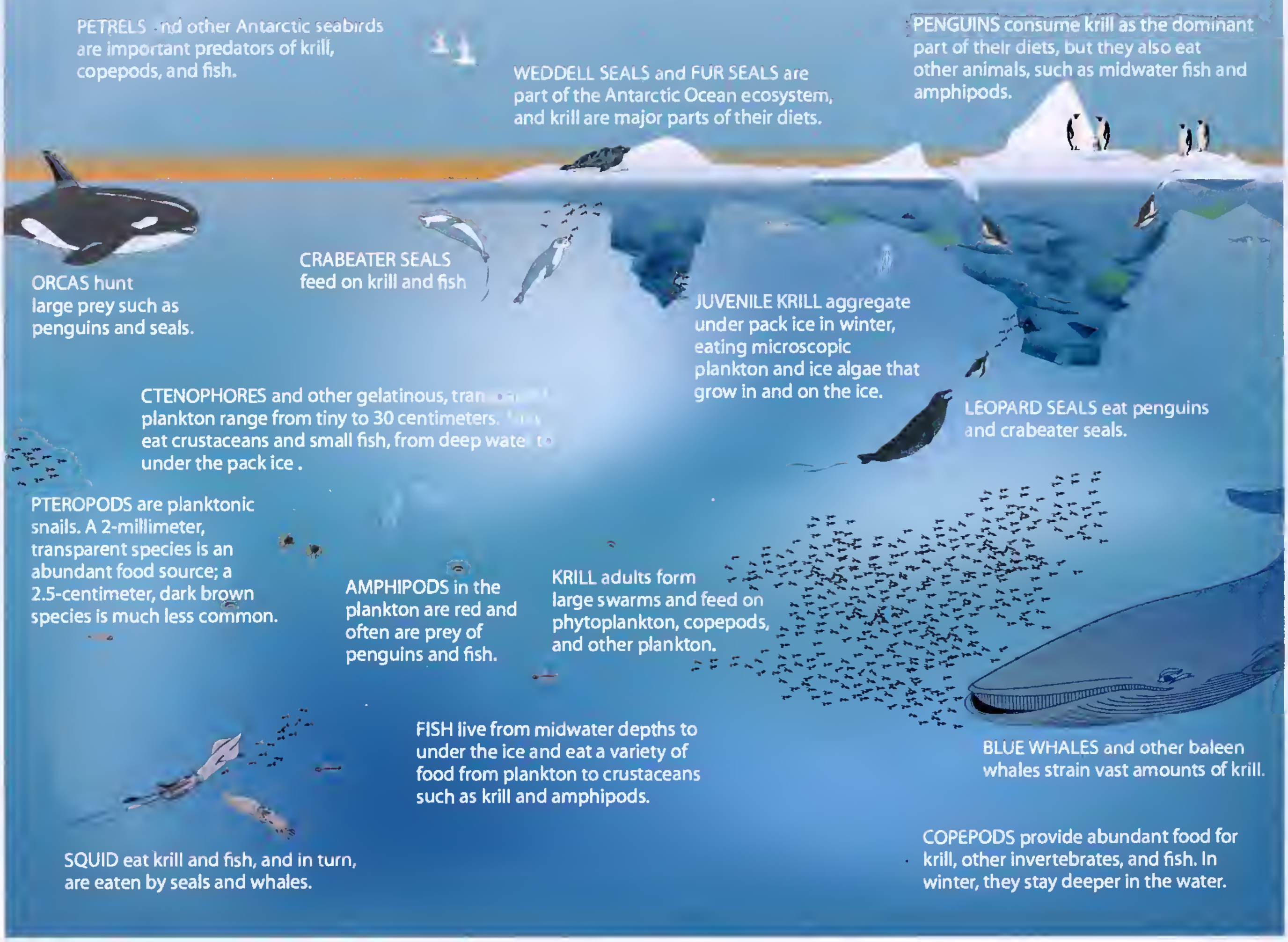


Jack Cook, WHOI Graphic Services

MARGUERITE BAY AND ENVIRONS, on the Western Antarctic Peninsula, was the research site for four Southern Ocean GLOBEC cruises. Inset: Antarctica and the southernmost tip of South America, where research vessels depart Punta Arenas, Chile, to cross to Antarctica.

The Antarctic ecosystem

Antarctic seas are extremely productive because phytoplankton grow abundantly during the extended daylight of summer and feed huge populations of krill. Krill are a key animal in this ecosystem, as food for top predators: whales, penguins, and seals. Winters have little light, no phytoplankton growth, and extremely cold temperatures, but a complex food web links a great variety of ocean animals.



Jayne Doucette, WHOI Graphic Services

agonally across the continental shelf and ends in fjord-like features up to 1,600 meters deep in the interior of the bay. Our principal goal was to discern how these features, along with water properties and currents in the region, conspire to allow krill to flourish and be retained in the area.

Coping with the chill

Working in the Antarctic fall and winter was challenging, and the scientists themselves had to learn to adapt. Temperatures during the fieldwork ranged from 0°C to -28.5°C (32°F to -19.5°F). As the late fall turned into winter, bitter cold and near perpetual night set in. The day was a brief, dim twilight. Sea ice covering the water made it very difficult to deploy and tow our instruments to sample ocean waters and marine life.

Seizing this rare opportunity to conduct research in these remote locations at these times, scientists had to coordinate a wide range of research spanning the spectrum of the region's physics and biology. It was the first time so many scientists had gathered to study so many aspects of the Antarctic.

To accommodate the amount and breadth of research, the scientists had to endure long cruises, 44 to 50 days, in frigid conditions and had to use two National Science Foundation research ships at the same time. One was the 308-foot icebreaker *Nathaniel B. Palmer*, which can operate in pack ice and clear a way. The other was the 230-foot, ice-strengthened research vessel *Laurence M. Gould*, which can come in contact with ice but not force its way through it.

In the fall of 2001, we worked mostly in open water, free of sea ice. In these conditions, the two ships could work independently. For instance, scientists studying

plankton and those studying penguins could travel to separate locations to do sampling needed by each group.

But conditions were much colder when we returned to the region in the fall of 2002—in fact, the coldest in 20 years of measurements there. Sea ice formed almost instantaneously, and we were often beset by icebergs that made it difficult or impossible to do our work, or even to get to sampling locations on a grid we had mapped out to ensure coverage of the bay. The ships had to remain together in convoy to get to work sites, with the icebreaker leading the way. Still, we persisted, huddling in our extreme-weather clothing, with the ships casting beams of light into the darkness.

Unprecedented observations

The Southern Ocean GLOBEC cruises resulted in a number of "firsts." An important accomplishment was to install arrays of long-term moorings in strategic locations across the continental shelf and inside Marguerite Bay. These moorings had sensors that measured water currents, temperature, salinity, and bio-optical properties (such as the clarity of the water) continuously over two years between deployment in 2001 and retrieval in 2003. Such moorings never before had been deployed on the Antarctic continental shelf, and they provided the first-ever measurements of currents there.

Current surveys based on instruments deployed from the ships revealed large circular eddies swirling on the continental shelf, which may help keep krill in the bay, where conditions favor their survival. The surveys showed that water from the fast-moving Antarctic Circumpolar Current, circulating just beyond the continental shelf, rides up onto the shelf, supplying warmer, more saline, nutrient-rich water into the Marguerite trough and bay. Such intrusions moderate winter conditions in the bay and enhance its fertility.

Oceanographers also found a previously unknown southward coastal current that flowed along Adelaide Island, into Marguerite Bay, and then south along Alexander Island. Our hypothesis is that deep and recirculating currents in the bay support krill reproduction, and the coastal current may move krill progeny along the coast to other areas.

Scientists and engineers also moored pressure-protected instruments on the seafloor, both on and off the continental shelf and in Marguerite Bay, to record marine mammal calls for a year at a time and open a previously inaccessible window onto cetacean life in this region.

Two automatic weather stations were installed on Kirkland and Faure Islands in the middle of Marguerite Bay. They continue to operate, providing the first continuous meteorological observations from this region of the Antarctic.

Tools to catch elusive prey

The aim of the biologists aboard the GLOBEC cruises was to survey krill and other plankton in the water and map where their populations are. To accomplish this, we needed a combination of tools and instruments.

Adult krill swim fast and are notorious for avoiding capture by the relatively small nets traditionally used by oceanographers. To circumvent this, high-frequency acoustics has become biologists' tool of choice for surveying krill. A transducer emits sound into the water. When sound waves, propagating at 1,500 meters per second, hit animals in the water, a portion of the energy is scattered back to the transducer.

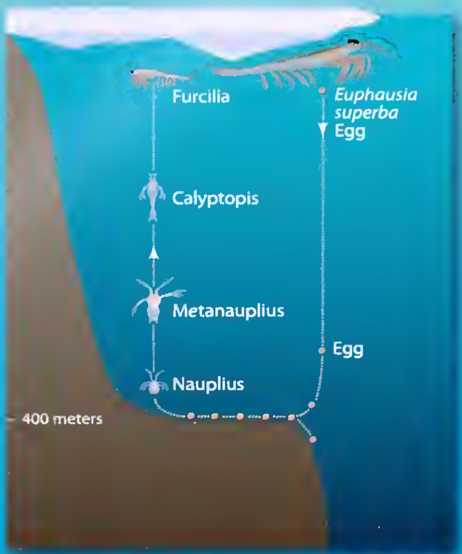
The acoustic signals give an indication of how much animal life is present at different depths, but they cannot identify what species are present. So, despite the krill's agility, we still use nets to collect samples needed to interpret the acoustic returns.

To map the distribution of krill and other plankton, we used a towed vehicle, the BIo-Optical Multifrequency Acoustical and Physical Environmental Recorder, or BIOMAPER-II. It is equipped with an acoustic system with five frequencies, a video plankton recorder system (VPR) to take pictures of the plankton, and sensors to measure water properties.

Stan Alesandrini

UNDER THE ICE—Melanie Parker and Kerri Scolardi (University of South Florida) dive to collect juvenile krill that aggregate under pack ice to feed on microzooplankton and ice algae.

A krill's life cycle



*Krill start life as eggs that sink and hatch in spring. They develop through larval stages as they swim to the surface, reaching the fourth (*furcilia*) stage by winter. Krill that hatch at the depth of the Antarctic shelf (300 to 400 meters) can swim back to surface waters before winter and find phytoplankton to eat before they use up their stored supplies.* Furcilia *that make it survive their first winter by feeding on algae and zooplankton on the undersurface of pack ice. But krill that hatch in water deeper than 500 meters may starve before they can swim back to the surface, and food.*

Jayne Doucette, WHOI Graphic Services

Robots and divers under the ice

We also towed a specialized net at different depths behind the ship to collect plankton that were later sorted and identified aboard ship. This net, the Multiple Opening/Closing Net and Environmental Sensing System (MOCNESS), has a 1-square-meter mouth opening that can be signaled to open and close separate nets to capture plankton at different depths without combining the samples. We equipped it with a strobe light to temporarily blind the krill so they could not see the net, thus reducing their ability to avoid it. We used an even larger MOCNESS trawl to collect the larger mid-water animals, such as shrimp and fish.

In winter, krill larvae and other plankton often are found living in or just under the bottom of pack ice. So we sent a small remotely operated vehicle (ROV) under the ice. It was tethered to the ship by a cable that transmitted power to the ROV and data from it. Operators could directly monitor and direct the vehicle, which was equipped with a VPR; water temperature, salinity, and depth sensors; and a tracking device to signal its location.

Finally, teams of divers conducted under-ice surveys of krill larvae and collected some of them for experimental studies back onboard ship to measure the krill's rates of feeding, growth, and respiration.

A krill's life

Antarctic krill, *Euphausia superba*, is the largest and often the most abundant of five shrimp-shaped euphausiid species that inhabit Southern Ocean waters. They grow to lengths of 6.5 centimeters and can live for seven to eight years—although most get eaten early in life, and few, if any, die of old age.

In most ways, the life history of krill is typical of crustaceans. Life begins as a fertilized egg that hatches into a larva called a *nauplius*. Then, as the larva grows, it goes through a series of larval stages (called *metanauplius*, *calyptopis*, and *furcilia*—several stages of each). When the larvae's exoskeletons become too small, they molt and grow progressively larger exoskeletons, until they become adults.

But in some other ways, Antarctic krill have an unusual life history, facing challenges inextricably linked to their environment. To survive here, they need not only the long light conditions of summer, but also the icebound sea of winter.

Scientists on the British Antarctic expeditions discovered 80 years ago that krill eggs sink to depths of 500 meters or more before hatching, perhaps to avoid predation near the surface. (That requirement fits nicely with the depths of the western Antarctic continental shelf.) But the larvae eventually have to swim back up to sunlit surface waters to find enough food (phytoplankton and zooplankton) to grow through their larval stages to adulthood.

Antarctic water is very cold, only 1°C to -1.8°C, and the cold temperature slows the krills' larval development. Krill eggs hatched in the austral spring only make it to the fourth, or *furcilia* stage, before winter sets in. By that time, pack ice covers the water, and no phytoplankton grow. Neither krill larvae nor adults have stored enough lipids (fat) to provide energy to see them through until spring. So how do they make it?

Survival tactics

Two field seasons of the Southern Ocean GLOBEC program in the Antarctic fall and winter have significantly improved our understanding of how krill survive the winter. Part of the answer is that krill larvae that reach the surface congregate in, or just under the bottom of, pack ice.

In the open ocean, anything that can be used as surface will be—to grow on, huddle on, feed on, or get caught on. In the pitted underside of the ice are phytoplankton, ice algae, microzooplankton, and organic detritus. We found that larval krill have flexible feeding habits and can eat this diverse, albeit scarce, buffet.

We found from shipboard studies that at least some larval krill are able to obtain enough food within and under the ice to meet their nutritional needs during the austral winter, though they could not find enough food to grow.

But they can delay their growth, molting, and development, or even suspend them for a time. They can even survive some period of starvation by digesting some carbon and nitrogen from their own exoskeletons and muscles.

Hot spots and cold spots

As for the adult krill, we discovered two "hot spots" where large populations of krill accumulated: Labeauf Fjord in Marguerite Bay and Crystal Sound just north of Adelaide Island. The krill in these areas occurred in a dense layer between 50 and 120 meters below the sea surface. We found another hot spot off the northern end of Alexander Island, a region of rough bottom topography. We are currently analyzing our data to explain these hot spots.

Not surprisingly, large numbers of seals, penguins, and whales also frequented these areas. While scientists on *Palmer* surveyed and counted krill, sea birds, penguins, seals, and whales, other investigators aboard *Gould* focused on experimental studies of seals and penguins. They temporarily captured a number of animals to measure their physiological properties and later released them. At the same time, they attached tags carrying temperature and pressure sensors and a transmitter that could send data via satellite back to a computer logging system.

The data recovered from tagged Crabeater seals and Adelie penguins revealed their diving and feeding behavior, and researchers discovered some movements that they hadn't suspected. For instance, Adelie penguins can dive to much greater depths and can travel farther and faster than scientists previously believed. Because the tags recorded top predators' activity for some time, we were able to see that hot spots of krill identified during the cruises continued to be focal points for the predators long after our ships left the area.

Elsewhere in the region, to our surprise, krill did not make up the majority of the zooplankton population. Instead, animals more typical of other ocean ecosystems, such as copepods (small crustaceans) and pteropods (small planktonic snails) dominated in the water. We still believe krill are the most important part in the chain linking primary phytoplankton producers to the top predators, but in some areas, other zooplankton play important roles in the ecosystem.

Peter Wiebe, WHOI

SHIP AT REST—The R/V Laurence M. Gould, *docked after the 2002 winter cruise, dwarfs the buildings of the U.S. research outpost at Palmer Station, Antarctica.*

The Antarctic frontier

There is still more to learn about the ecosystem. What about the adult krill? Large adults were abundant in 2001, when the weather was milder. They were largely absent—as were the larval krill—during the second year, when conditions were colder. Where did they go? Was this related to the early onset of pack ice formation in 2002?

Even with the icebreaker, we could not reach several places, because the ice pack was impenetrable. In these areas, we suspected, the adult krill would be found.

Newer technologies, though, will soon help us meet the challenge of the Antarctic. For example, autonomous vehicles (robotic vehicles that don't need tethers) and moorings equipped with biological sensors could gather data under the ice when ships cannot take us there. Some of these vehicles and moorings are now being developed. (See "Sensors to Make Sense of the Sea," page 68.) A more powerful icebreaker now being developed specifically for Antarctic research will provide better access to ice-covered seas.

The Antarctic region is a formidable and sometimes forbidding place in which to work, but it is also a region of great beauty. Even more, it is susceptible to climate change. It is a linchpin in the forces that cause global climate variability—since melting polar ice will create cascading effects through the world. It will be important for us to be able to anticipate the impacts of climate change on the Southern Ocean ecosystem. To do that, we anticipate that future research programs will build on GLOBEC's legacy of an integrated, multidisciplinary ecosystem approach, and we will do more work in the harsh, dark Antarctic winter.

Growing up near the seashore in central California, Peter Wiebe developed a love for and a curiosity about the oceans at an early age. As a youth, he spent hours free-diving in the Monterey Bay area, and he assembled his first scuba gear in 1954. His undergraduate studies took him to northern Arizona, a region whose oceans disappeared 40 million years ago, thus making him too late to study them firsthand. He returned to California and the Scripps Institution of Oceanography to obtain a Ph.D. in biological oceanography, and then came to Woods Hole Oceanographic Institution in 1969. Now a senior scientist at WHOI, his interests have focused most recently on the dynamics of zooplankton populations on Georges Bank and on krill living on the continental shelf region of the Western Antarctic Peninsula—two components of the U.S. Global Ocean Ecosystem Dynamics Program. For his efforts leading the GLOBEC program, the National Oceanic and Atmospheric Administration awarded Wiebe its Environmental Hero Award for "tireless efforts to preserve and protect the nation's environment."

Run Deep, But Not Silent

A new tagging device lets scientists 'go along for the ride' into the underwater world of whales

By Peter Tyack, Senior Scientist
Biology Department
Woods Hole Oceanographic Institution

Whales are among the most elusive animals that humans have ever hunted. Pursuing whales across the seas and centuries, whalers made careful observations of whale behavior whenever and wherever they surfaced. But sperm whales, for example, spend about 95 percent of their time beneath the waves. Studying five percent of their behavior was enough to learn how to kill them, but it has taught us very little about how they live.

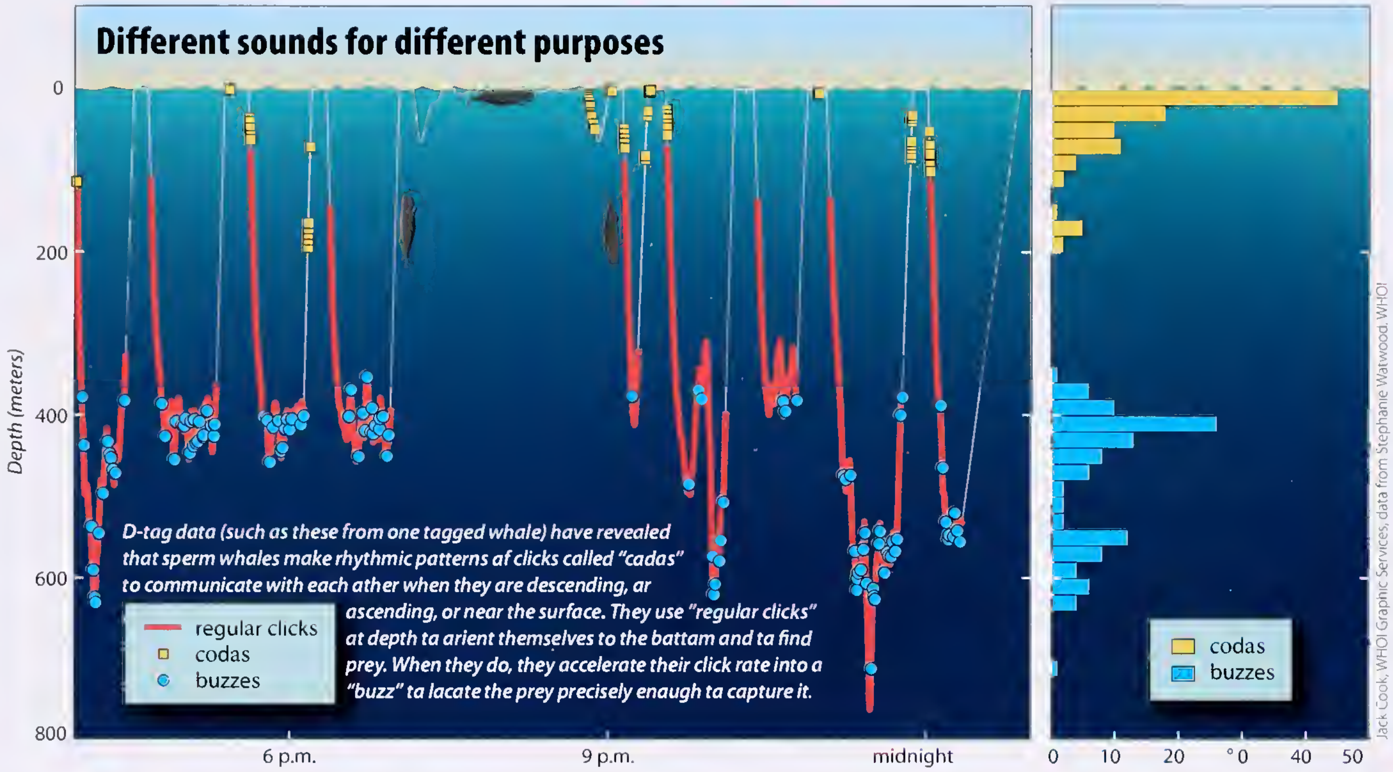
But now, for the first time in history, we can accompany a whale on its dive, hear what it hears, and observe its normal, natural, previously hidden behavior in the depths. Working closely together, scientists and engineers have created an innovative device—the digital acoustic recording tag, or D-tag. It attaches to a living whale and records nearly everything that happens on its dives, without disturbing the animal. (See "Playing Tag with Whales," page page 57.)

On land, behavioral scientists spend years carefully observing animals such as wolves, lions, or chimpanzees to build up a detailed record of how they behave in response to social or environmental circumstances. Often the researchers remain hidden, or they acclimate the wild animals to their presence, before they can trust that their observations reflect natural behavior.

We cannot do that with whales. We can't be unobtrusive, because boats can't be hidden. And we can't observe whales for long, because most of the time, we can't see them at all. Scientists have had no practical way to follow along on a

Marco Ballardini, BluWest

TAG TEAM—Researchers succeed in the challenging task of using a 40-foot carbon-fiber pole to attach a revolutionary digital recording tag, or D-tag, to an elusive whale during its brief stay at the surface between dives. The tag attaches with suction and records sounds and whale movements during several dives. It releases automatically after about 12 hours.



sperm whale's epic dives, 600 to 1,200 meters down into the cold, dark depths, on their all-consuming mission to search for enough food to keep their massive bodies fueled. Until now.

Pioneering whale studies

Whales live in a world of sound, not sight. Like bats, they send out and receive sound signals and are guided through the sea by what they hear—using both sounds reflected back from objects and sounds made by other whales. Sound is the currency of their lives; they rely on it for knowing where the bottom is, for finding food, and for communicating with each other.

Researchers also use sound for locating whales. Nearly 50 years ago, biologist William Schevill and physical oceanographer Valentine Worthington at Woods Hole Oceanographic Institution were the first to record the sounds of sperm whales, using underwater devices called hydrophones. WHOI biologist William Watkins made enormous advances in identifying which sounds are made by which species of marine mammal.

So careful were these pioneering scientists' methods that we still use their results 45 years later. They still represent some of the best data sets available, accurately measuring and attributing sounds to the different whales that made them, and I have avoided many wrong turns by being attuned to this resource.

With hydrophones, scientists could listen to sounds in the sea and begin to know where, what kind, and how many whales there are in an area. But what the whales were doing below the surface has remained hidden.

The D-tag's origin and evolution

Ecologists place tags on a variety of animals to track their movements, and they have tagged marine animals, too: whales, dolphins, seals, turtles, and even a great white shark. Such tags record depth a few times each minute and can transmit data only when near or at the surface, giving scientists a record of the tagged animal's location and depth over time.

I came to WHOI originally to develop a small tag for captive dolphins that would light up when a dolphin made a sound, allowing us to tell which individual made which sound. It worked well for captive dolphins, but I had not considered using it in the wild. In the early 1990s, a graduate student at the University of Guelph named Andrew Westgate developed the first tag that could be used on wild porpoises to record time and depths of their dives. Unlike earlier tags used on seals, it was not on a collar, but temporarily attached to the porpoise. It was designed to fall off the animal and be recovered by researchers who could then download the data.

His success led me to pursue an archiving tag for wild whales, which would have a greater capacity to measure behavior and sound. WHOI engineer Mark Johnson began to build a tag that would record not only times and depths, but also any sounds in the water—both the whale's sounds and sounds in the whale's environment. Over the last five years he has refined the D-tag into a remarkable device that attaches to a whale with suction cups and stays on during a dive, while not disturbing the animal—a critical consideration if you

want to observe normal behavior.

The D-tag records and stores what the animal is doing and what its environment is like. Beyond time, depths, and sounds, the tag records temperatures in the environment surrounding the whale; and the whale's pitch, roll, speed, and direction. It measures this information 50 times a second.

After up to 12 hours and multiple dives, the tag releases its suction automatically, floats, and sends out a radio signal so we can recover it aboard ship. So much data is recorded about the whale's dive that it can take three hours to download.

Applying the tag

The success of the tag depends on being able to attach it to a whale, of course, and that depends on having a way to reach a sperm whale from a small boat, while keeping some distance away. While working with North Atlantic right whales, WHOI biologist Michael Moore and engineer Richard Arthur developed a cantilevered, 40-foot, carbon-fiber pole, which researchers in small boats can use to deliver sedatives, ultrasonic transducers for sigmoidoscopies, or a suction tag to a whale at the surface.

Without this invention, we couldn't tag the whales. Even with it, it's still a difficult process that requires luck, patience, decent weather, and some measure of fortitude. We find ourselves in tiny boats, trying to sneak up on large and often intractable wild animals to stick something on them with a long pole, during the small fraction of time they are at the surface. Any one of our "subjects" could swim away from us or dive at any time. The work is exciting on many levels.

What whales say and hear

Like us, whales use different sounds for different purposes. Data from the D-tag show us that sperm whales don't waste time or energy in travel. They spend very little time at the surface, dive nearly straight down to very deep water, then spend quite a bit of time at this "foraging depth," hunting for food, before coming nearly straight up again to the surface.

When whales begin a dive to find and capture prey, they start producing sounds called "regular clicks" roughly once per second, at depths of several hundred meters. They use the regular clicks, it seems, to orient themselves. For most regular clicks, the tag records sound echoes reflecting from both the ocean's water surface and the bottom.

Sperm whales also seem to use regular clicks as a sonar to find patches of prey. But as they close in on their prey (mostly squid), they rapidly accelerate their click rate into a sound we call a "buzz," which seems to be used to locate the prey precisely enough to capture it.

Whales also use sound to communicate with each other. The D-tag has revealed that they make rhythmic patterns of clicks called "codas" not only when they are near the surface, but also during the start of their descents and the end of their ascents, when they interact with one another during their dives. We have tagged two to three sperm whales at the same time and have discovered, after downloading data from the recovered tags, that the whales dived in synchrony, on similar dive tracks to the same depth. They maintained a steady distance between each other, apparently by listening to each other's regular clicks.

Using the D-tag on a smaller toothed whale called a beaked whale, Mark Johnson and WHOI biologist Peter Madsen, working in my lab, have been able, for the first time, to record and hear not only the sounds a whale makes when foraging, but also the echoes reflecting off the prey, returning to the whale, and recorded by the tag. The tags have even captured the sound of prey being captured.

Noise pollution

Whales also hear, and react to, sound from other sources, including boat engines, military sonar, or airguns used to explore for oil and gas beneath the seafloor. We don't yet know the exact range of frequencies they hear, but the D-tag will allow us to investigate whales' responses to different ambient sounds. Ongoing studies on whale ear anatomy by Darlene Ketten at WHOI can give information on what frequency range they are likely to hear (See "How to See What Whales Hear," page 59.) There is growing concern that human-generated sound may interfere with the whales' navigation, feeding, communication, and lives.

During a sperm whale cruise that happened to coincide with the invasion of Grenada, Bill Watkins and I found that sperm whales become silent when exposed to sonar sounds, and when exposed to airguns, they have reduced rates of buzzes associated with catching prey. We don't know yet how much of an interruption of their normal feeding this can cause, or the possible ramifications it may have on reducing the energy available for their growth and reproduction. The D-tag can tell us what happens on multiple dives of a single animal and also lets us compare dives of many different animals, so that we can build up a library of a population's behaviors.

The future of this work is immensely exciting. We will be able to learn what whales have known for eons—what their lives are like. We hope it will also help to protect them from unintended impacts of seagoing humans.

Peter Tyack writes: "My parents had me sleeping in the sail bag of a daysailer in Manchester Harbor at seven months old, and I have always loved going to sea. Intrigued by animal behavior and wanting to do field research, I went to Harvard in the early 1970s, as the fields of behavioral ecology and sociobiology came of age. I initially majored in biological anthropology, fascinated by primate social behavior. But a course with WHOI biologist William Schevill on cetaceans convinced me that marine mammals were just as fascinating and offered many more unexplored research opportunities. From then on, I studied acoustic communication and social behavior of whales and dolphins. Donald Griffin and Roger Payne made it possible for me to do Ph.D. research at Rockefeller University on the songs of humpback whales. After that, I came to WHOI, where I have happily worked ever since."

Playing Tag with Whales

Engineers overcome nightmarish specifications to create a dream instrument

By Mark P. Johnson, Research Engineer
Applied Ocean Physics & Engineering Dept.
Woods Hole Oceanographic Institution

The challenge of designing a device to learn what marine mammals do on dives is the stuff of dreams for an electronics engineer.

In the spring of 1999, the time was right to build the digital acoustic recording tag, or D-tag—an instrument to record the movements of whales and the sounds they make and hear in the ocean. Miniature cell phones, MP3 players, and Personal Digital Assistants had created a demand for small, lightweight, dense memory components and batteries. In many ways, the tag is just like an MP3 player, PDA, and home medical monitor rolled into one, and then sealed against seawater and pressure in the deep ocean.

Helped by electronics engineers Tom Hurst and Jim Partan at WHOI, and a summer student studying mechanical engineering, Alex Shorter, we put together the first D-tag in record time. Driving us was an opportunity in the summer of 1999 to use the tag on endangered North Atlantic right whales, as part of an effort to understand why they are hit by ships all too often.

A small, chock-filled package

The D-tag is actually a miniature computer with its own microprocessor, memory, and software. It records sound using one or two hydrophones (underwater microphones) with better-than-CD quality—not only the sounds made by the tagged whale but also sounds from other whales, noises from boats, and all of the sonars and sound sources in the area.

The tag also contains a digital compass, a pressure sensor (the underwater equivalent of an altimeter) to measure the depths of a whale's dive, and an orientation sensor that measures the animal's pitch and roll. The pitch sensor records the whale's body undulations fast enough for us to count each beat of its tail fluke.

Think of the displays in the cockpit of a small plane: The tag sensors are measuring similar things but under water. Everything gets stored in digital form. The tag has as much as six gigabytes of memory, enough to record continuously for a full day.

Putting it on, getting it back

To keep out the saltwater and survive harsh treatment from socializing animals, the tag has a plastic skeleton and is sealed inside a thick urethane bag. To keep the weight and size down, the tag does not have a pressure housing (the aluminium bottle normally used to protect electronics from high pressure in the deep ocean). Instead, we spent a lot of time at the WHOI pressure-testing facility choosing electronic components that would withstand pressures of up to 3,000 pounds per square inch—that's 200 times atmospheric pressure at sea level. As a re-

Tom Kleindinst, WHOI Graphic Services

INVENTIVE COLLABORATION—Engineer Mark Johnson (right) and biologist Peter Tyack work together to learn about whale behavior, using Johnson's D-tags to record whale movements, depth, and sounds on dives. Back in the lab, D-tag data tell the story of the whales' dives, from their swimming behavior to the kinds of vocalizations they use while foraging.

Photo courtesy of the University of La Laguna, Canary Islands

TAGGED—D-tags were placed on deep-diving pilot whales in a collaborative project with the University of La Laguna, Canary Islands, to study their behavior during dives and in response to ferries and whale-watching boats.

sult, the entire electronics unit measures about 4 by 1.5 by 1 inches and weighs about 5 ounces—no problem for even a small whale to carry.

To allow us to retrieve the tag after it comes off the whale, it is equipped with flotation so that it rides atop the surface like a buoy, and a tiny radio beacon, so we can find it by tracking its radio signal.

Of course, the tag is no use at all if it doesn't stick to the whale, and so we have spent a lot of time studying suction cups. For three years, we tested every suction cup we could find to figure out which would hold best. Finally, we decided that we had to build the cups ourselves to get the right mix of strength and softness—to be tenacious and yet not hurt the whale. Using a mold built by the WHOI shop, we now make cups out of medical-grade silicone that work incredibly well.

New heights (and depths) for D-tag

That first caffeine-powered field season in 1999—working with northern right whales in the Bay of Fundy with the International Fund for Animal Welfare—was just the start. Since then, D-tags have been used on more than 30 field expeditions all over the world.

We have worked with D-tags on sperm whales in the Gulf of Mexico and Italy, on manatees in Belize, on narwhals in northern Canada, on beaked and pilot whales off the Canary Islands, and on humpbacks off Australia and Cape Cod. Colleagues have taken the tags to Antarctic islands to study fur seals and to California and Canada to work on blue whales and gray whales.

D-tags have gone on the deepest dives ever recorded on a marine mammal and have discovered the sounds made by two of the world's most mysterious whales: Cuvier's and Blainville's whales are little-known mid-sized beaked whales whose only claim to public attention is their occasional mass strandings associated with sonar use during naval maneuvers. Many marine mammalogists have never seen these whales alive. They are very shy and usually live way out in the big blue. They are so inconspicuous at the surface that you can sail right by them unless the sea is flat and you know what to look for.

We have learned that these whales are incredible divers. Using D-tags, we have recorded dives 85 minutes long with depths of up to 1,900 meters. Amazingly, the tag is sensitive enough to hear echoes from objects in the water, insonified (lit up—but with sound) by the click sounds made by the beaked whales.

An increasingly noisy ocean

Marine mammals are one of the least understood groups of animals. D-tags allow us to explore the world the way marine mammals do: with sound. (See "Run Deep, but Not Silent,"page 54.)

Meanwhile, human noise in the oceans is increasing by the decade as more and faster ships are made, as oil exploration moves into deep water, and as navy ships with high-power sonars patrol for submarines. There are ample signs that these noises can disrupt marine mammals, even causing mass strandings and death. But without a more complete understanding of how whales use and sense sound, we cannot begin to figure out which noises are problematic and at what levels (See "How to See What Whales Hear," page 59.)

My hope is that this device will eventually help us learn how to be better neighbors under water.

Mark Johnson grew up in New Zealand, that southern paradise with a beach for every person (and sheep). He was always close by the ocean—which defined everything. A box of transistors thrown out by an electrician neighbor lured him into the world of electronics, sound, and music. He studied engineering at the University of Auckland and pursued a Ph.D. working on anti-noise (an electronic method to cut down noise) at the Acoustics Research Center in Auckland. Taking a "holiday" job at WHOI in 1993, Johnson was drawn into Peter Tyack's marine mammal group. Now in the twelfth year of his holiday, the D-tag project has sent him traveling around the world and given him the opportunity to work with some amazing animals—and biologists. When not following whales, he gets as far away from the ocean as possible: Deserts and mountains tend to stay still under your feet.

How to See What Whales Hear

Biomedical imaging reveals new insights into marine mammal ears

By Darlene Ketten, Senior Scientist
Biology Department
and Kate Madin, Science Writer
Woods Hole Oceanographic Institution

On summer nights, if you sit quietly at the edge of a field or watch the edges of the light pools around street lamps, you will see bats swooping through shadowy darkness in search of moths or other flying prey. They detect and catch their targets through echolocation, or biosonar, the animal equivalent—and precursor—to man-made sonars.

Bats generate signals in their nose and throat that produce echoes, which the bats monitor to determine the size, shape, speed, and direction of their prey, as well as other objects in the area. Biosonar is also how they navigate in dark caves. Bats' large, distinctive, convoluted, mobile ear flaps are critical for the fine-grain acoustic analysis they do during echolocation.

Now flood that field with seawater and make it not only dark but profoundly deep and filled with a myriad of exotic creatures and objects. That is the dim and complex world in which whales live.

Although whales and dolphins are air-breathing mammals, they spend approximately 85 percent of their time under water. Compared to sound, light does not penetrate water well, and it is not surprising that whales and dolphins rely primarily on hearing rather than sight to sense their environment and communicate. The *Odontoceti*—toothed dolphins and whales that hunt fish, squid, and other prey—evolved parallel abilities with bats, actively using clicks and pulsed sounds for underwater echolocation.

However, there is one very striking difference between bats and dolphins. The latter appear to have no outer ears. Dolphins and whales abandoned external ears as a concession to better underwater mobility. Still, they do have ears buried inside their heads: fascinating ears in fact, with exceptional range that operate at extraordinary depths.

With the help of a common medical tool—biomedical computerized tomography, more commonly known as CT and MRI scanning—we are beginning to get inside the heads of whales and dolphins. Using biomedical imaging techniques, we can thoroughly explore just how their ears are constructed—and see how and what they hear.

Into the inner ear

Whale hearing is difficult to study by conventional methods. Whales are large, elusive, diverse creatures, and research on most species is substantially restricted because of their endangered status. One approach to learning how whales hear is reverse engineering, which is essentially the clockmaker's child approach to science. We can examine stranded animals to determine not only what may have caused their deaths, but also, literally, what makes them tick.

Virtually all mammals have the same three basic ear components: an external ear flap, or pinna, is connected via an ear canal to the middle ear cavity, which has an eardrum and bony lever system

Tom Kleindinst, WHOI Graphic Services

READY TO SCAN—Postdoctoral Investigator Soraya Moein Bartol and Senior Research Assistant Scott Cramer position an Atlantic white-sided dolphin, which stranded and died, on the WHOI CT scanner bed before imaging, while CT technologist Julie Arruda (front) examines previously generated images.

for amplifying sounds, and then an inner ear, which transduces sounds into neural impulses. In marine mammals such as seals and otters, the pinnae are reduced to allow them to swim faster; in whales and dolphins, the sleekest and fastest of marine mammals, these outer ears are gone completely.

Traditionally, investigating the inner workings of whales and dolphins has been done by dissection. But to examine the parts, you are compelled to disassemble the relationship of those parts, which is fundamental to understanding their effective operation. Even worse, conventional dissection requires time, especially when the subject outweighs you by several hundred pounds. By the time you can get to many structures, they have deteriorated beyond recognition.

We knew there are robust, complex inner ears buried deep in dolphin and whale heads, but we did not know how sound gets into those inner ears.

Seeding an innovative idea

At WHOI, we took a different approach; or rather, we updated the traditional one. We still dissect, but our dissections are digital. Biomedical scanning rapidly and non-invasively reveals in great detail the internal structure of the object or animal that is imaged. We can use imaging techniques to see into most living animals. To image rare and deep-ocean materials, we do not need to remove them from their protective containers.

Above all, we see the synergy of internal structures. For ill or stranded animals, we can locate and examine pathologies or traumas non-invasively—precisely what scanners were designed to do for humans.

The idea of using a CT scanner to probe inside marine mammals was a radical idea a decade ago. In 1998, with funding from the Andrew W. Mellon Independent Study Award program at WHOI and from The Seaver Institute, the first large-scale study of marine mammal auditory systems using computerized tomography was undertaken using CT and MRI scanners in area hospitals. This study demonstrated the extraordinary potential of scanning for marine mammal research, since it allowed high-resolution anatomical surveys of many individual animals in an unprecedentedly short time.

Courtesy Darlene Ketten, WHOI

VISIBLE HEARING—This 3-D CT scan image of a blue whale's inner ear (18 millimeters in diameter) shows typical mammalian inner ear structure, including a spiral cochlea and the vestibular system that controls balance.

In 2000, the Office of Naval Research, and particularly Admiral Paul Gaffney, former Chief of Naval Research, furthered the effort by providing start-up funds to install a high-capacity CT scanner at WHOI that was dedicated exclusively to marine research.

How CT scanners work

CT scanners use X-rays to produce an image of density differences of internal structures. The denser an object, the less X-ray energy is transmitted through the object to the detectors, and the brighter the object in the image. For this reason, bone appears white, air looks black, and soft tissues are varying shades of gray in an X-ray.

In common single plane X-rays, such as chest films, the detector is a sheet of film that is exposed by a single pulse from the X-ray tube. Consequently, the output is a flat image in which one structure overlays another.

CT scanners employ a bank of electronic detectors that monitor the X-ray attenuations from multiple pulses and positions, as the X-ray tube moves through an arc around a patient or specimen. This complex, multi-dimensional matrix of attentuations is then deconvolved to generate images that represent the attenuations in thin cross-sections.

It is, in a very real sense, a virtual dissection, slice by slice, of all structures. The WHOI scanner allows us to image slices as thin as 0.1 millimeters and to detect attenuation differences that are several thousand-fold.

Using scanning techniques to look at whale and dolphin ears, we can study the geometry and composition of ears and other head tissues from microscale to macroscale and thereby gain insights into what and how they hear. We also see sometimes how they were damaged.

The impacts of sound

Sound is energy. The louder a sound an animal can hear, the greater the potential for damage to its ear. Some loss of hearing from day-to-day wear and tear is normal; some is excessive and avoidable, as far too many of us are well aware from exposure to loud music, power tools, or other intense sound sources.

However, just to complicate matters, not every sound is equally dangerous to all ears. Because different species have different hearing capacities, what is imperceptible to one animal may be annoying or even harmful to another. An ultrasonic dog whistle is imperceptible to humans but clearly heard by any normal dog or cat.

Even more important, the effects of sound can range from the physical, with actual damage to parts of the auditory system, to behavioral: sounds so disturbing that animals abandon normal activity, such as feeding and breeding, or even alter their migration paths.

Both physical and behavioral effects potentially have serious impacts on individuals or on entire species. Consequently, understanding hearing in marine mammals is not just a matter of curiosity, but fundamental for marine conservation and possibly even for the survival of some species.

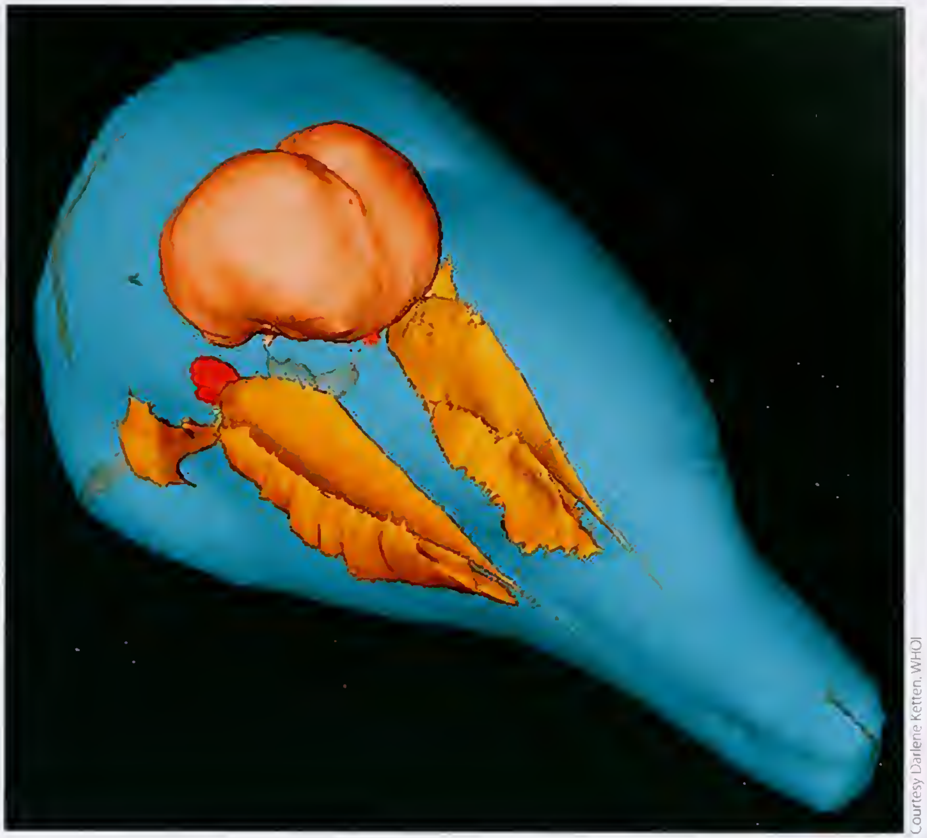
Ships, sonars, and strandings

The ocean is a naturally noisy place. Sounds are generated by volcanism, wind, waves, earthquakes, and by animals themselves. However, all human activities in or near the water are adding to this natural suite of oceanic sound.

In recent years, mass strandings of whales—in Greece in 1995, the Bahamas in 2000, and the Canary Islands in 2002—have focused attention on the possible effects of man-made sound in the oceans. In those cases, multiple U.S. and NATO ships were engaged in exercises employing multiple and intense sonars in narrow straits.

While the presence of these ships and the exceptional sound field produced by the exercises clearly coincided with the strandings, we are not yet able to determine exactly what mechanism led to them. We examined many of the stranded animals using our scanner system and found distinctive traumas, but the damage is not strictly acoustic. Rather, it appears to be more consistent with stress than directly sound-induced.

In other cases, however, we have found damage to ears, often from aging or long-term noise exposures that clearly impaired the animals' hearing and therefore their ability to function in the wild. At this point, we do not know precisely what noises are most harmful, either directly or indirectly, to any marine mammal species, but this is a critical area of research that we must pursue intensely and rapidly.



INTERNAL EARS—A 3-D image generated from a CT scan highlights selected tissue groups of a bottlenose dolphin's head. It shows the relationships of the exterior skin (blue), brain (pink), inner ear bones (red), and specialized auditory fats (orange). The fats form paired lobes inside the head along the jaw and are very similar in shape to the outer ear flaps (pinnae) of bats.

The inside story of dolphin ears

One of our first major discoveries answered the original mystery of the missing external ears: Without external pinnae and no obvious canal, how does sound enter dolphins' heads and how does it get to the inner ears?

Researchers had speculated that since dolphin inner ear bones were located near their jaws, perhaps the soft tissues and bone of the jaw played a role. Unfortunately, that was hard to prove, because fat tissue in the area deteriorated rapidly and the relationships between tissues were disrupted as soon as they were cut during dissections.

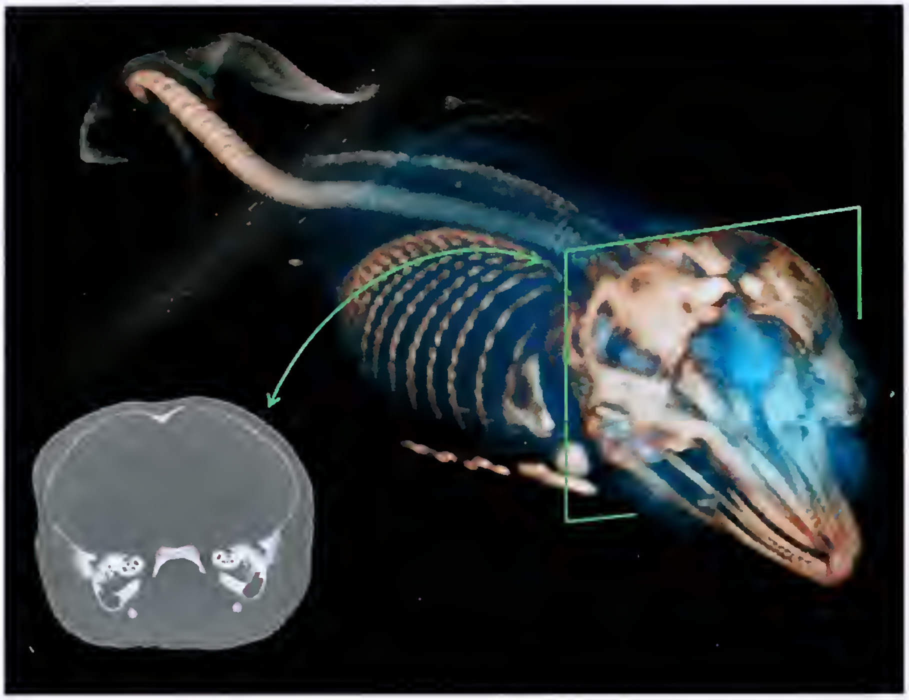
CT scanning gave us the first undisturbed images of this region. In fact, it provided the critical clues: The fatty lobes near the jaw were connected to the ear and had shapes similar to bat pinnae. In effect, bats and dolphins seem to have parallel ear evolution. Dolphins have pinnae that are just as complex and large as bats, but they are internal—an advantage under water both hydrodynamically and functionally; these specialized fats have acoustic properties similar to seawater. Consequently, in terms of both shape and physics of sound in water, they are the aquatic analog of land mammal outer ears that were designed to capture and conduct airborne sound.

The speed of sound in water

Scanning also allowed us to measure the locations of dolphin ears in situ, which explained why the ears are spread so far apart in dolphin heads. Dolphin ears are widely separated to accommodate the speed of sound in water, which is 4.5 times faster than in air.

One clue to determining the location of a sound source is the difference in arrival time between your ears. Humans have trouble locating sound sources under water, because, acoustically, our heads "shrink" nearly five-fold because of the increased speed of sound through water. As dolphins evolved, they expanded their heads and inter-ear distances to match sound speeds in water, which explains their extraordinary ability to localize sound sources three times better than humans.

Scanning also provided the first data on the inner ear of the true behemoths of



Courtesy Darlene Ketten, WHOI

A SECRET SEEN—This 3-D image shows an intact, near-term fetus discovered inside an Atlantic white-sided dolphin that stranded and died. The fetus's flippers are folded and its ribs are lightly mineralized, but the cross-section reveals fully matured ears.

the oceans. Blue and fin whale ear bones are massive, approximately the size of a human brain case and at least twice as dense. To demineralize these ear bones to dissect them by traditional methods would take more than two years. With scanning, we can digitally slice them to see inner ear features in less than an hour.

Anatomy reveals hearing capacity

Although all mammal ears have the same basic parts, there are some important differences among species in some structures that account for differences in hearing capacities. No two species have exactly the same hearing ability. Different animals can detect different frequency ranges and have different sensitivities at any one frequency. Most mammals hear frequencies well above the range of human hearing, termed ultrasonics. Some also hear well at very low frequencies, even the seismic sounds generated by earthquakes.

To study both normal and abnormal hearing, our laboratory has used the scanner to image all parts of the auditory system of more than 30 species of marine mammals. Each ear from an unknown hearer is compared with those from species with well-documented hearing characteristics. In particular, we construct "maps" of the stiffness and mass of ear components of animals whose frequency ranges are known and compare the stiffness and mass of newly imaged marine mammal ears to calculate their resonant frequencies. Thus, we can determine the critical commonalities for hearing in all mammals—as well as critical differences for specialized hearing like echolocation and for hearing under water instead of in air.

We also make maps this way for the few marine mammals species for which hearing has been tested. These are our model controls, as our maps are consistent with audiograms or hearing curves of tested animals. The new ear maps from untested species have led to the discovery that whales have some of the widest hearing ranges of any mammal and that some species are capable of hearing at seismic or hyper-ultrasonic frequencies.

We now know that some species of whales have a 12-octave hearing range, compared to eight in humans. Some whales hear well down to 16 hertz (or cycles per second), versus our lower limit of 50 hertz, while others hear as high as 200 kilohertz. The typical high-frequency cutoff for humans is 16 kilohertz. For bats, it is 60 to 70 kilohertz.

This work is coordinated also with other WHOI laboratories doing basic research on marine mammal sounds, diving, and foraging behaviors, as well as applied research on acoustic devices to warn highly endangered species of impending ship strikes. (See "Run Deep, But Not Silent," page 54 and "Whither the North Atlantic Right Whale?" page 29.) So far, we know there is no single sound bite that is perceptible or harmful to all marine creatures, but with luck, we may be able soon to provide guidelines that will help preserve some of them.

Sam Ogden

Darlene Ketten is a neuroethologist, studying how behavior is linked to sensory system anatomy in various species.She started out to be a Romance language specialist but discovered as an undergraduate that biology opened many more mysterious worlds inside the heads of exotic animals. While working on her doctorate at The Johns Hopkins Medical Institutions, she began using computerized tomography (CT and MRI scanning) to explore how biomedical imaging techniques could be used to investigate how inner ears in different species are structured and coupled to the rest of their heads. This led to micro-imaging work at Harvard Medical School to improve diagnosis of causes of hearing loss in human ears. In 1997, she joined the Biology Department of Woods Hole Oceanographic Institution and brought her combined backgrounds of neuroethology and neuroradiology to bear on modeling hearing in marine mammals based on their specialized auditory system anatomy, and most recently on analyzing potential effects of man-made noise in the oceans. In addition to basic research, she does specialty forensic analyses of heads and necks of stranded animals for NOAA National Marine Fisheries Service investigations. Although much of her work involves mathematical models and 3-D software, she has never lost her preference for working directly on the "wetware."

CT scan menagerie

Peering into whale heads—without the loss of tissue and time that normal dissections cause—was the initial motivation for using a CT scanner for marine mammal research, but our current scanner has had more than its share of other types of species and objects. Some of the specimens scanned here, particularly to assist the work of other researchers, have been remarkable.

Scan data obtained at the WHOI facility have proven invaluable for investigating everything from diagnosing sinus infections in live, sneezing seals to imaging shark balance organs, coral reef fish swim bladders, flippers of all forms, fractures in great whale jaws, coral reef growth patterns, pressurized ocean sediment cores, and, most exotic of all, the complex mineral substructure of hydrothermal vent chimneys.

Animals as small as grass shrimp have been scanned to help modelers determine how much sound energy large groups of similar invertebrates, called krill, reflect at different frequencies. Acoustical oceanographers use such models to determine whether reflected signals at sea actually represent deep layers of millions of krill in patches throughout the oceans.

Land creatures that also have been scanned in the last two years include tigers, hedgehogs, bats, and even an elephant and a hippopotamus (parts only—they are just a tad too big for whole ones to fit on the table).

In 2005, the scanner is scheduled to move into a new facility on the WHOI Quisset campus. Moving the scanner is not trivial; in fact, the scanner has a good deal in common with the megalithic money on Yap. Both are giant toroids that, once in place, are daunting to shift.

The scanner move will require two engineers, a rigging crew of up to six workers, and two weeks of disassembly and reassembly time. Still, the effort will be worth it, as the new facility incorporates overhead hoists and tracks connecting the scanner room with surgical and storage facilities that will allow us to transport, scan, and understand an even wider range of creatures that may come our way.

Photos by Tom Kleindinst, WHOI Graphic Services

MEGALITHIC TO MINIATURE—The WHOI CT scanner is a unique resource for scientists studying internal structures in animals. Both marine and terrestrial animals have been scanned to let scientists "look inside." Among specimens examined this way are (clockwise from lower left): a mandible (lower jaw bone) of a North Atlantic right whale, prepared for scanning by MIT/WHOI graduate student Regina Campbell-Malone and CT technologist Julie Arruda; a large core section of coral, with an intricate internal canal structure that once housed coral polyps, positioned on the scanner bed by scientists Anne Cohen and Hanumant Singh with Arruda; a Siberian tiger head, for research by Edward Walsh of Boy's Town Research Hospital to determine what tigers hear and how they protect themselves from their own extraordinary roars; and a live bat, carefully cushioned and sedated, watched by biologist Darlene Ketten, for ONR-funded research by James Simmons of Brown University to help understand bat ears and echolocation.

Revealing the Ocean's Invisible Abundance

Scientists develop new instruments to study microbes at the center of the ocean food web

By Rebecca Gast, Associate Scientist
Biology Department
Woods Hole Oceanographic Institution

Microbes. They are invisible to the naked eye, but they play a critical role in keeping our planet habitable. They are everywhere, in abundant numbers, but are still difficult to find. They come in a multitude of varieties, but too often are difficult to distinguish from one another.

Wherever there is water (fresh or salt), there are usually microbes—microscopic, single-celled organisms. In the ocean, they form an unseen cornucopia at the center of a food web that ultimately nourishes larger organisms, fish, and people.

Their fundamental role in the ocean's food supply makes them critical targets for study, and scientists would like to know much more about them. They would like to identify them and count them. They would like to learn more about how marine microorganisms (part of what we call plankton) eat, grow, reproduce, and interact with other organisms. They would like to determine how changes in the ocean might affect the microbial communities' vitality and viability.

Finding minuscule life forms in a seemingly infinite ocean isn't trivial. But in recent years, oceanographers have been developing new techniques and instruments to identify and count marine microorganisms. Year by year, we are learning more about them and discovering that they are even more numerous, varied, and important than we thought.

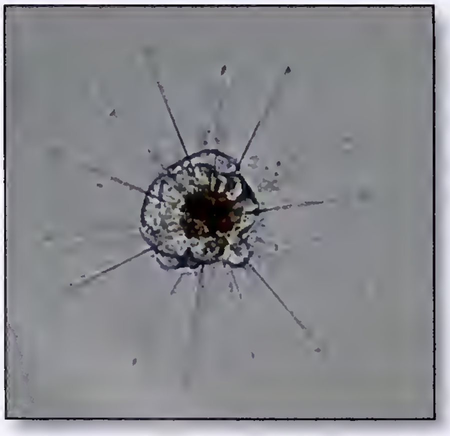
A diverse microbial community

Some marine microbes are bacteria, or prokaryotes—simple cells with no specialized organelles, which are among the smallest of living things. Others are eukaryotes—larger and more complex cells with a nucleus, mitochondria, and other organelles.

Eukaryotic microbes, also called protists, include both producers, such as algae, and consumers, such as protozoa. They thrive in a variety of habitats—living suspended in the water, in bottom sediments, or on other objects. They form communities, or assemblages, of different species that photosynthesize, consume each other, and are, in turn, consumed by other things in the ocean's food web.

In the last few years, we have considerably advanced our knowledge of the struc-

A Gallery of Protists



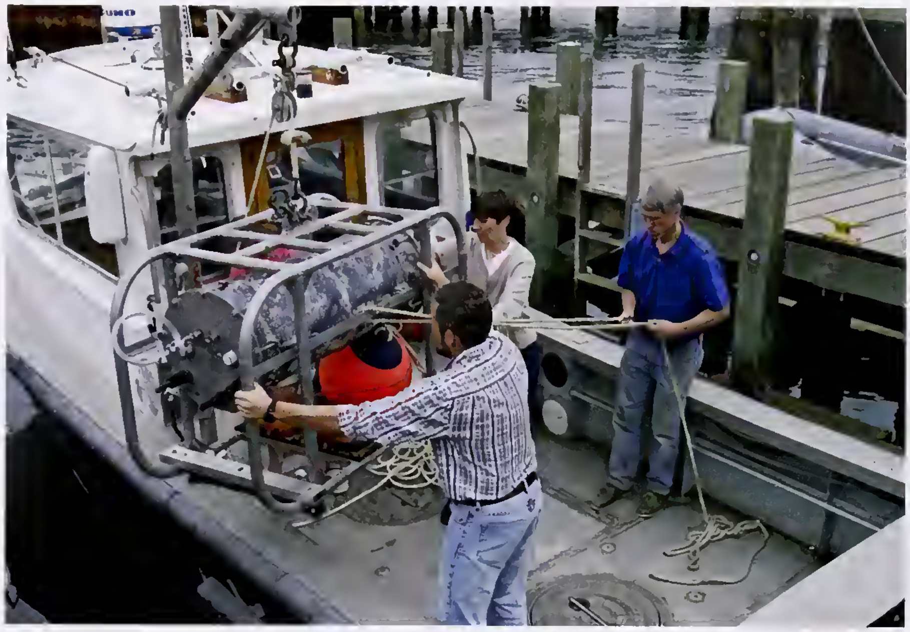
A heliozoan is heterotrophic, meaning it consumes both plant and animal matter.

Tintinnids have transparent, vase-like shells for protection. Thye are consumers of a wide variety of cells and detritus.

Diatoms (such as Corethron*, above) are at the center of the food web, using photosynthesis to live, grow, and multiply.*

ture and function of these assemblages—particularly planktonic assemblages that we sample by collecting the water they inhabit. We now know that these plankton assemblages are diverse, composed of species with widely different sizes, growth rates, and nutrition. Not surprisingly, we know more about the larger protists (greater than 100 microns) than the smaller ones (under 20 microns). Larger protists are easily visible using light or electron microscopes. They have features that remain intact throughout procedures to sample, preserve, and examine them, which can break or distort cells. These features are often lacking in the smaller organisms; and if they are present, they are harder to see and characterize.

Identifying protists has always involved some type of microscopic analysis, with someone looking at the shapes, or morphology, of the cells. But now we also use molecular methods—techniques that give scientists the ability to detect and identify the presence of even small protists based upon their DNA in water samples. Scientists have begun to describe the genetic composition of communities of species that live and interact in the same water. Our next objective is to overcome several technical challenges so that we can routinely monitor changes in protist populations over time.


Tom Kleindinst, WHOI Graphic Services

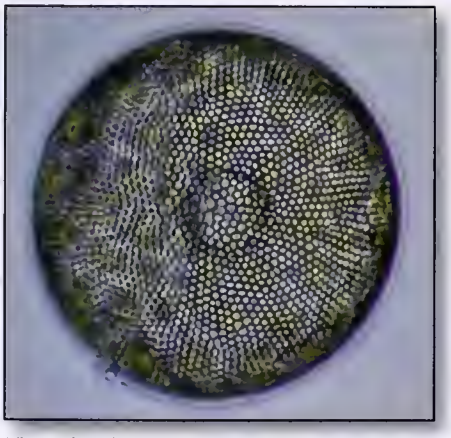
SHORE TO SHIP—WHOI researchers Alexi Shalapyonok, Heidi Sosik, and Robert Olson (left to right) carefully load the FlowCytobot onto a WHOI research vessel for installation on the seafloor at the Martha's Vineyard Coastal Observatory. The instrument counts and identifies protist cells in the water, and the data is transmitted via undersea cable back to shore.

Sampling the invisible

So far, all of our detection and identification techniques, both morphologic and molecular, have relied on collecting samples from remote sites and analyzing them in laboratories. But these techniques don't give us all the information we need.

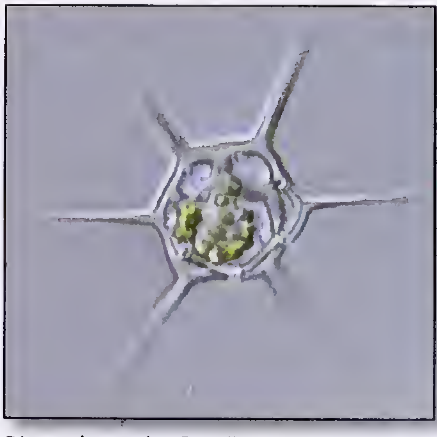
Collecting samples from ships means physically taking separate water samples, at separate times, in separate places. Samples taken this way are, quite literally, just single samples—of one location at

Single-celled organisms are critical links in the ocean's food web. Though ubiquitous and abundant, their microscopic size make them hard to sample and study. These protists, all found in Antarctic waters, are between 20 and 100 micrometers.

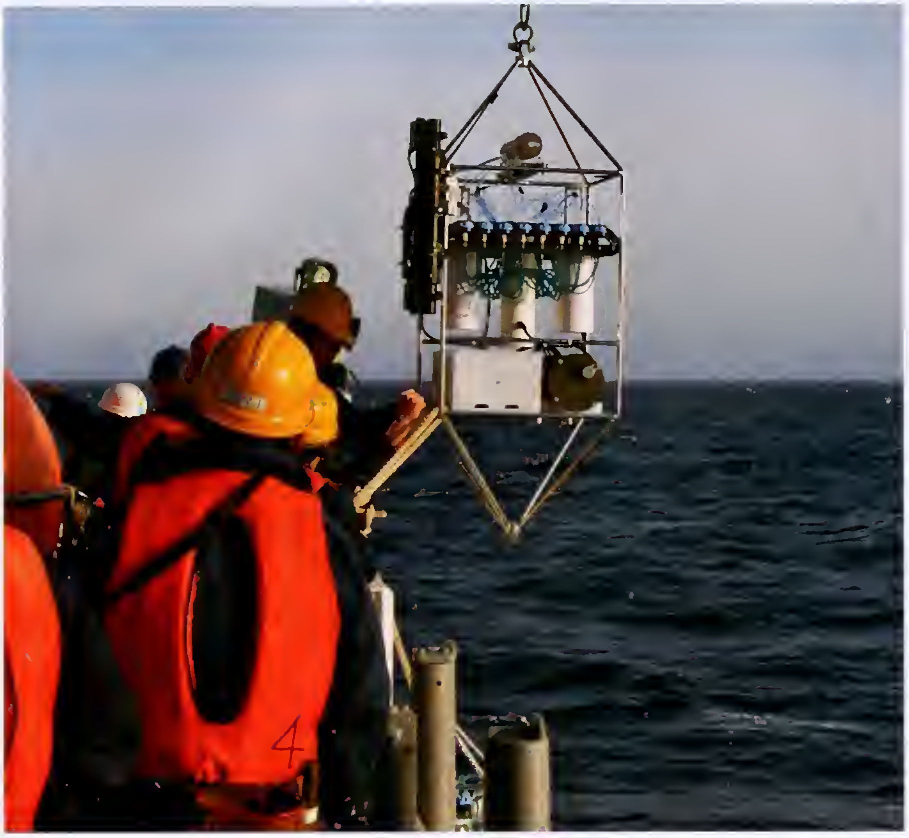


Viewed end-on, the diatom Coscinodiscus *is a study in symmetry and pattern, reminiscent of a sunflower's seeds.*

The dinoflagellate Dinophysis*, plump and harmless-looking, produces a toxin that causes diarrhetic shellfish poisoning.*


Photos by Dawn Moran, WHOI

Dictyocha*, a silicoflagellate, has an intricate, internal glassy skeleton and a starry shape that helps it avoid sinking.*



Craig Taylor, WHOI

OVER THE SIDE—The Submersible Incubation Device hangs from a cable, ready to be moored on the sea bottom, where it will take samples of surrounding seawater and measure photosynthesis in the ocean.

one time. They don't provide a continuous picture of protists in a given area of the ocean. And they don't allow us to detect how the protists respond to rapidly changing environmental conditions.

What researchers want is the ability to collect and analyze samples over long time periods in the ocean; to have a continuous sampling and recording procedure, and to obtain data in as close to real time as possible.

Overcoming engineering hurdles

Several technical challenges, however, still make it difficult to remotely detect and count microbes in their own environment. One is the number of organisms, or microscopic cells, in a given water sample. In most marine planktonic environments, microbes are present in low numbers and organisms targeted for study may only be a small proportion of the total population. To overcome this low density, researchers in the laboratory must often concentrate several liters of water into a much smaller volume for analysis by passing it through filters designed to retain the protists, then resuspending them in smaller volumes for analysis.

Once water samples are collected and concentrated, microbes can be analyzed in several ways, so automated systems must be designed to accommodate the analysis method. For instance, if scientists want to use only the organisms' genetic material to identify them, collection systems must be able to break open cells and collect their DNA. If they want to study the whole organisms, though, the systems must keep the cells intact.

In fact, researchers are already developing instruments that can either detect a genetic signal from a microbial population or monitor one of its biological activities—and do it autonomously, without requiring scientists to be on the scene.

The instruments can be programmed to collect water samples over periods ranging from hours to months and spaces ranging from inches to miles—depending on the particular microbes and biological activities scientists want to study. The instruments inject water into flexible bags containing a solution that preserves cells for later examination.

SID, ESP, and FlowCytobot

Three examples of instruments for remote analysis of marine microbes have been developed to solve many technical problems.

The Environmental Sample Processor, developed by Chris Scholin at Monterey Bay Aquarium Research Institute, attaches to a mooring anchored to the ocean bottom and collects and preserves water samples. It extracts nucleic acids from the protists in the water and detects specific organisms by their DNA. It can also preserve samples for microscopic analysis in the laboratory. Researchers have already used it to detect species that cause harmful algal blooms and to distinguish types of planktonic larvae in the ocean. It will soon have even greater capacity to detect and distinguish organisms.

The Submersible Incubation Device, a moored instrument developed by Craig Taylor at WHOI, determines levels of photosynthesis in the water around it by robotically measuring carbon dioxide taken up by phytoplankton in the samples. Up to 50 of these experiments can be performed before the instrument needs to be removed from the ocean to analyze the samples and determine what species are present.

A third instrument, FlowCytobot, is a submersible flow cytometer— a device that counts single cells flowing through it. Developed by Robert Olson at WHOI, it is also anchored to the seafloor near the coast. It counts and analyzes microbial cells in the water continuously for up to two months. FlowCytobot identifies microbes by the way they scatter light,

or by the way certain pigments in the cells emit fluorescent light. (See "Little Things Matter A Lot," page 12.) Because it samples continuously, scientists can see changes in plankton populations over time that cannot be detected by traditional sampling.

A coastal observatory network

The ultimate goal is a continuous, remote system that can detect, distinguish and count microbes in the environment. In the laboratory, scientists can do all these things by filtering samples, identifying DNA within them, and examining microbes under microscopes. But designing, programming, and building a system to carry out all of these steps remotely is a challenge.

One of the difficulties is that DNA analysis requires heat, which requires power. Remotely deployed instruments depend on batteries for power, and adding batteries quickly makes instruments too heavy, big, and costly to build. To overcome this hurdle, scientists have sought a viable alternative: developing long-term installations of instruments powered by cables from a nearby shore.

In recent years, several coastal ocean observatories have been built that have cables linking power nodes on the ocean floor with shore-based facilities. One of these is near Woods Hole at the Martha's Vineyard Coastal Observatory (MVCO). Instruments plugged into seafloor nodes receive power from the cables and transmit data back via the cables. This level of available power has stimulated the development of new biological sensors and methods that will let scientists take measurements continuously and accurately.

We are developing several instrument modules, for example, into the FlowCytobot automated system at MVCO (http://www.whoi.edu/insstitutes/coi/facilities/mvco.htm) The system will detect microbial cells, identify them genetically, and obtain accurate counts of particular species. It will let us monitor specific microbial populations that play significant roles in the food web and detect changes taking place daily.

The development of new sensors is also important to national efforts to build an infrastructure of ocean observation systems. Ocean observatories are the wave of the future in many fields of oceanography. Some will monitor coastal water; others will monitor the open ocean. Many already exist, and many more are being planned through several national programs. These programs will incorporate existing coastal observatories into a network, expand their research capabilities, and build more observatories at key coastal sites. We will use the observatories, each with seafloor cables supplying power, to collect and share information on a previously invisible microbial world—the broad group of tiny cells that control the coastal ocean's food supply.


Kim Fulton-Bennett, ©2004 MBARI

TIRELESS UNDERSEA WORKER—The robotic Environmental Sample Processor (ESP) lifts off the deck and begins its journey to the seafloor off Monterey, Calif. It will be moored there for a lengthy stay and take repeated samples of protists in the water.


Mark Dennett, WHOI

Biologist Rebecca Gast uses molecular methods to study the microscopic ocean. An associate scientist in the WHOI Biology Department, she examines the ecology of single-celled non-bacterial organisms, or protists, in the marine environment. Her work is often based in the Antarctic, where she studies protists in seawater, sea ice, and slush. She is interested in their diversity, distribution, and abundance, and how their proteins function in the extreme cold. Becky received her Ph.D. from the Department of Molecular Genetics at Ohio State University in 1994, and then came to WHOI as a postdoctoral scholar, where she has remained, keeping warm between visits to the ice and slush. In other projects, she studies symbiotic relationships of protists—where they occur and how they function. She is developing techniques to detect human pathogenic organisms (*Giardia* and *Cryptosporidium*) and invertebrate parasites (Quahog Parasite Unknown or QPX, a parasite in clams) in coastal ocean waters.

Sensors to Make Sense of the Sea

An expanding variety of sensors is changing they way we monitor dynamic ocean systems

By Scott Gallager, Associate Scientist
Biology Department
Woods Hole Oceanographic Institution

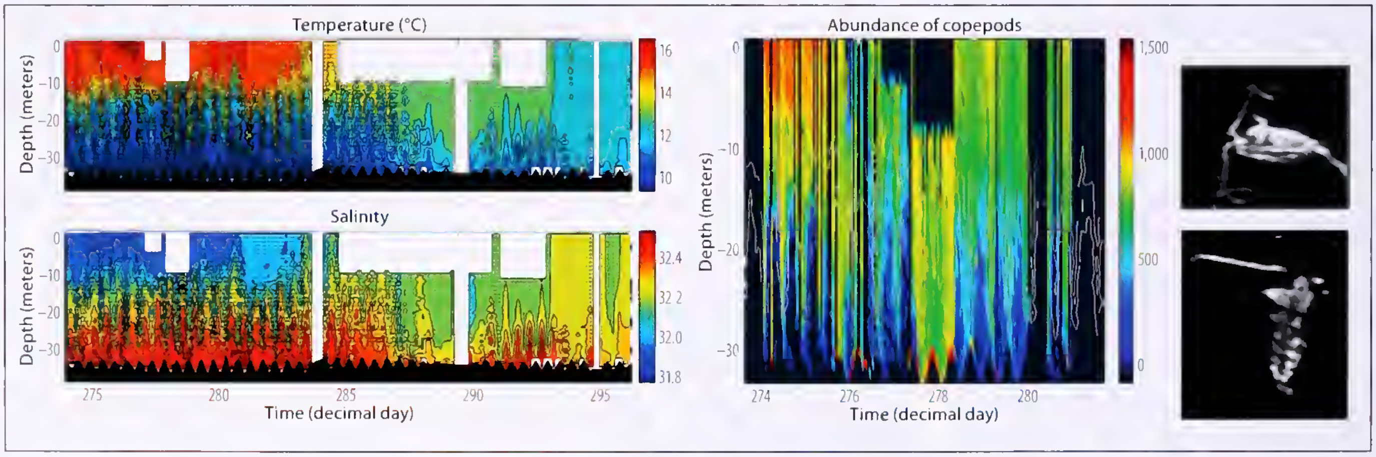
In science, the key to understanding any situation is careful observations and measurements. The key to observing and measuring, however, is being there—in the moment—and that has always proved challenging for oceanographers.

It is difficult and expensive to go to sea, hard to reach remote oceans and depths, and impossible to stay long. Like scientists in other fields, oceanographers use sensors to project their senses into remote or harsh environments for extended time periods. But the oceans present some unique obstacles: Instruments are limited by available power, beaten by waves, corroded by salt water, and fouled by prolific marine organisms that accumulate rapidly on their surfaces.

The oceans also surpass the limits of human observation at both extremes. It takes a long and large perspective to measure the exchange of greenhouse gases between Earth's entire atmosphere and oceans, over seasons or decades. On the other hand, chronicling the transfer of gas molecules at the interface between air and water requires a nanosecond-short, millimeter view. Once again, sensors can extend observations to detect phenomena beyond human capabilities. But it takes a wide spectrum of sensors and platforms to survey whale populations and their global migrations, while simultaneously collecting information on the microscopic plants and animals that whales eat.

Today, rapid advances in micro- and nanotechnology, biotechnology, computing power, and sensor integration are fueling development of a new generation of low-power, cost-effective, high-precision sensors that will withstand extended deployments in harsh environments and be able to relay data in real time. What's more, these sensors will be mounted on an expanding variety of observatory platforms that provide unprecedented access: satellite imaging systems, autonomous underwater vehicles carrying sensors on wide-ranging surveys, and ocean observatories with cables that continuously transmit power to instruments and send their data back.

In July 2003, the WHOI Ocean Life Institute and Deep Ocean Exploration Institute, along with the National Science Foundation and the Office of Naval Research, sponsored a workshop called

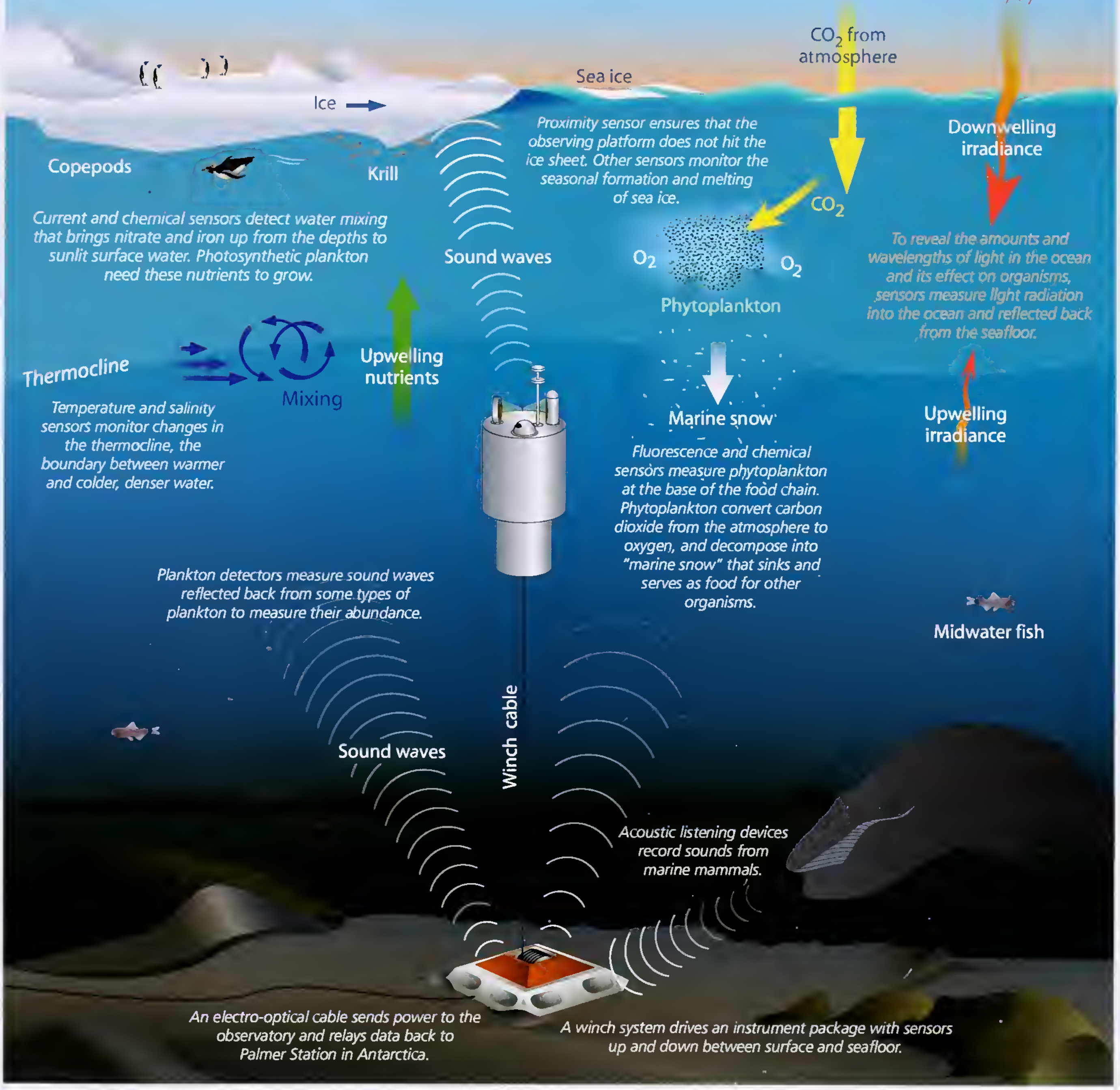


OBSERVING THE SEA FROM SHORE—A variety of sensors on ocean observatories provide running data logs on changing conditions in the sea. At left, temperature and salinity data from the seafloor to the surface off Martha's Vineyard over three weeks (day 274 to 296), collected by the Autonomous Vertically Profiling Plankton Observatory (AVPPO), show distinct water layers at the start that become less distinct. (Saltier and warmer waters are red; colder, fresher waters are blue.) At right, a video plankton recorder on the AVPPO captures images of tiny planktonic animals called copepods, while compiling a record of copepod abundance over three weeks (middle). The data shows that during a passing storm (days 277 and 278), the copepod population swam down to keep away from surface waves.

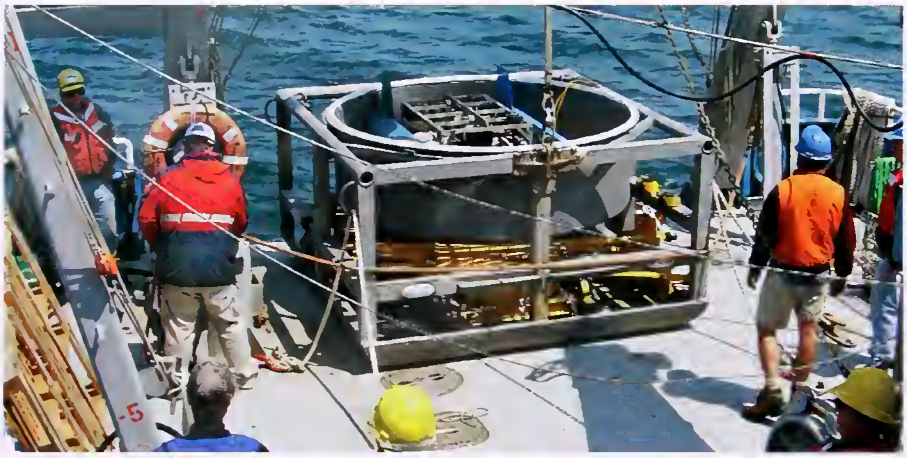
Monitoring An Ecosystem

The Polar Remote Interactive Marine Observatory (PRIMO), scheduled to be deployed off Antarctica in 2006, will be the first cabled observatory capable of remaining under the ice for a year. It receives power from and sends data back through an electro-optical cable to Palmer Station in Antarctica. A winch system drives an instrument platform up and down between surface waters and the seafloor. It is equipped with instruments that measure salinity, temperature, depth, oxygen, water motion, sound, water turbulence and clarity, light, nutrients, chlorophyll, organic matter, the amount and types of phytoplankton, zooplankton, and larger animals present, along with the platform's own orientation—all to help reveal the complex interactions and dynamics of the fertile ecosystem in the Southern Ocean.

PRIMO is a collaborative project, led by Vernon Asper of the University of Southern Mississippi and Scott Gallager of WHOI.



Jayne Doucette, WHOI Graphic Services


Andrew Girard, WHOI

OBSERVATORY OVERBOARD—Scientists and crew aboard R/V Connecticut *lower the Autonomous Vertically Profiling Plankton Observatory (AVPPO) to the seafloor. The AVPPO carries instruments that record changing conditions in the coastal ocean, including its temperature, salinity, motion, levels of chemicals and dissolved gases, and the numbers and kinds of organisms living in the area. Data are relayed via cable to the WHOI Martha's Vineyard Coastal Observatory.*

"The Next Generation of in situ Biological and Chemical Sensors in the Ocean." It brought together ocean scientists and engineers with colleagues from the fields of biomedical technology, nanotechnology, and electrical engineering to explore new approaches and possibilities for ocean sensors.

The workshop presented an exciting vision and road map for sensors in the not-so-distant future that will allow quantum leaps in what we can observe and discover in the oceans. Our decade-old dream is now becoming a reality: to be able to observe phenomena in the ocean continuously, on all scales and in real time, and to be able to interact with sensors in the oceans—all from shore.

Testing the waters

Oceanographic sensors come in all flavors: They measure light, temperature, sound, mass, or chemical species. All of these senses will be needed to gain the full picture of all the interacting physical, biological, and chemical dynamics going on in the oceans.

Scientists have a fairly good idea of what we need to measure in the ocean. To study ocean pollution, for example, ocean chemists require sensors that detect synthetic compounds, such as those derived from plastics and petroleum products, automobile exhaust, storm and sewer runoff, pesticides, fertilizers, surfactants, and chlorofluorocarbons (Freon). To understand how chemical cues help organisms find food, or initiate mating or spawning, we need sensors to identify complex organic molecules and learn their concentrations and persistence in the environment.

To determine whether the oceans can absorb excess greenhouse gases, we need sensors that measure climatically and ecologically important gases such as carbon dioxide, methane, hydrogen, hydrogen sulfide, and radon. Other chemical sensors can indicate how much carbon dioxide is converted by photosynthetic plankton into organic carbon, and how much of this sinks to the deep ocean—to mitigate the buildup of greenhouse gases, or to feed hungry populations of deep-sea organisms. All these sensors, along with others that measure seawater properties such as temperature, salinity, and turbulence, will let biological oceanographers begin to see how ecosystems work and how they change over microseconds to decades.

Identifying the inhabitants

To learn how organisms respond to changing habitats and interact with each other, oceanographers first need to determine when and where species are present, from bacteria to whales. To identify organisms over the scale of microscopic plankton (micrometers) to a full ocean (thousands of kilometers), scientists need systems that integrate optical and acoustic sensors, which give complementary information.

Sound propagates far in water, providing information over long distances. But it travels in long wavelengths that yield only low spatial resolution. Light, on the other hand, scatters quickly in water, but travels in short wavelengths, giving us high-resolution information on small organisms and their "spheres of influence" —a few body lengths around them.

Some integrated systems already exist. One is the Bio-Optical Multifrequency Acoustical and Physical Environmental Recorder, or BIOMAPER-II, developed at WHOI, which was used recently to survey krill populations around Antarctica. (See "Voyages into the Antarctic Winter," page 48.) Towed behind a vessel, BIOMAPER-II carries an acoustic system to detect small marine organisms such as krill or plankton, a video plankton recorder to take pictures of them, and other sensors to measure water properties.

But just knowing the locations, concentrations, and types of species is still not sufficient. Scientists also need information on organisms' feeding, growth, and reproduction. Integrated systems will soon carry sensors that sample, analyze, and identify biological molecules—among them DNA, proteins, enzymes, and lipids—that signal biochemical activities.

The Environmental Sample Processor, developed by Chris Scholin at Monterey Bay Aquarium Research Institute, is a working example. Attached to a mooring on the seafloor, it extracts nucleic acids from water samples and detects specific organisms by their DNA. (See "Revealing the Ocean's Invisible Abundance," page 64.)

An expanded toolkit

Exciting additions to our sensor arsenal are already being developed. To begin to measure tiny "needles" of dissolved gases, trace metals, elements, and nutrients in the "haystack" of the oceans, several new approaches show great promise.

Laser-Induced Breakdown Spectroscopy (LIBS) uses a laser to vaporize tiny amounts of a material and determine its elemental composition based on the light spectrum it emits. WHOI scientists are collaborating with the Army Research Laboratory to develop oceanographic sensors using LIBS.

Raman spectroscopy uses laser light to cause tiny samples of water to vaporize and the molecules in the water to vibrate. That changes the spectrum of light scattered from the molecules, thus revealing many high molecular weight compounds in the water, including large organic molecules such as lipids, proteins, and amino acids. Raman spectroscopy can also be used to detect dissolved carbon dioxide.

It may soon be possible to identify microorganisms in seawater by scanning it with light and measuring the way they scatter light at different wavelengths. Miniaturized equipment to make this measurement already exists, and advances in mathematical analysis techniques (known as spectral deconvolution) may allow us to detect the species, concentrations, mass, chemical compositions, and even nucleotides (components of DNA) in seawater samples.

Scientists are just beginning to measure chemicals in the extremely harsh conditions of hydrothermal vents and seeps, where the high temperatures (up to 400°C or 750°F) and corrosive nature of hydrothermal fluids make them almost impossible to sample directly with sensors. A promising technology for these conditions, called voltammetry, simultaneously detects a variety of chemical ions including oxygen, hydrogen sulfide, iron, and manganese.

Voltammetry employs electrodes to scan seawater with a range of voltages while measuring the electrical current output occurring in response to the voltage scan. This output is recorded as a spectrogram: a graph of multiple peaks in which the location and height of the peaks are proportional to the types and amounts of ions in the seawater.

'Wiring' the oceans

But all these sensors are of little value unless they can get out into the ocean and stay there. Autonomous underwater vehicles (AUVs) are one way to accomplish that mission, but oceanographers have also been developing exciting new cabled observatories that provide continuous power to plugged-in instruments and two-way communications to scientists ashore. Developed and developing observatories are being located to study various ecosystems, including productive coastal areas, harbor entrances, or regions under polar ice.

At WHOI, the Martha's Vineyard Coastal Observatory will soon become the homeport of a new observing platform called the Autonomous Vertically Profiling Plankton Observatory (AVPPO), which is designed to observe daily, seasonal, and annual changes in the coastal Atlantic Ocean ecosystem (left). A winch system drives a platform on a 15-minute trip from the seafloor to the surface. It is equipped with a range of instruments—35 sensors in all—that measure salinity, temperature, oxygen, water motion, water turbulence and clarity, light, chlorophyll, organic matter, the amount and types of zooplankton and phytoplankton present, along with the platform's own orientation in the water. These measurements can be correlated with weather and storm events and will help us monitor the coastal ecosystem's response to climate and other changes.

A similar instrument, the Polar Remote Interactive Marine Observatory (PRIMO), will soon be installed under the ice in the Southern Ocean and cabled to shore from Palmer Station on the western peninsula of Antarctica. It will be the first cabled remote observatory in the harsh Antarctic environment and our first long-term, real-time look at this fertile ecosystem that supports a wealth of marine life.

PRIMO will transmit data via cable and satellite and give researchers and students a direct link to critical phenomena and events, including storms, currents, sea ice formation, and the spring phytoplankton bloom that fuels an entire food web. It will also provide clues on how this delicately balanced ecosystem might respond to the receding ice edge and other changes related to climate. Like other observatories, PRIMO will be used in concert with AUVs by including docking facilities for AUVs in the future.

We have entered a new era with a changing paradigm of how we sample the ocean. We soon will "wire the oceans" with instrumental "eyes, noses, and hands"—which can't help but dramatically expand our understanding of what's going on in the oceans. Stay tuned, the best is yet to come.

Tom Kleindinst, WHOI

Scott Gallager has been interested in the inhabitants of lakes and oceans since his college days. His interest in engineering and electronics goes back even further: While still in high school, he published his first paper, "A Color TV You Can Build," in *Popular Mechanics*. He earned a bachelor's degree in biology and environmental sciences at Alfred University and a master's degree in marine sciences at Long Island University, and then worked at WHOI as a research assistant, associate, and specialist while completing a Ph.D. in biology at Boston University. After a postdoctoral position at Dalhousie University, he returned to WHOI, where he is an associate scientist in the Biology Department. His interests have led him to use electronic and computer technology to study how planktonic organisms live in and adapt to their environments, and their functional morphology and biophysics. He works in coastal Atlantic, Arctic, and Southern Oceans, building instruments to remotely monitor ocean ecosystems. He often talks to teachers and students and has originated a Boy Scout merit badge program in oceanography.

Down to the Sea on (Gene) Chips

The genomics revolution is transforming the way scientists can study life in the oceans

By Mark E. Hahn, Senior Scientist
Biology Department
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A half-century ago, James Watson and Francis Crick (aided by Rosalind Franklin and Maurice Wilkins) discovered the double-helical structure of deoxyribonucleic acid (DNA). Other scientists soon showed how DNA—through a triplet code of nucleotide bases on the DNA "spiral staircase" and through ribonucleic acid (RNA) intermediaries—instructs cells to assemble essential life-sustaining proteins. These discoveries opened the door to a new understanding of life by revealing the genetic "blueprints" that underlie the ability of organisms to grow, survive, and reproduce.

A revolution in biotechnology ensued, giving scientists methods to isolate and identify genes, make millions of copies of them, and determine their sequences of nucleotide bases. Together, the accelerating pace of biotechnological advances and the exponential increase in DNA sequence information ignited an explosion in molecular biology and led to the emergence of a new field: genomics. These advances were initially applied in the biomedical arena, leading to new information on the genes responsible for heritable diseases, the molecular signatures of cancer cells, the biology of human pathogens, and genetic factors that influence an individual's sensitivity to drugs or toxicants.

Now, the genomics revolution has reached the oceans. New genomic techniques are being used to find previously unknown life forms in the oceans; to learn how species, and genes themselves, evolved over Earth's long history; to understand the genetic tools that allow species to adapt to diverse and often harsh environments; and to investigate species' responses to pollutants. Genomics gives marine scientists powerful new ways to address age-old questions about life in the oceans.

What is genomics?

Genomics is more than simply determining the sequence of nucleotides in an organism's genome (the entire set of genetic information contained within a cell's DNA). It is a new approach to questions in biology, distinguished from traditional approaches by its scale. Rather than studying genes one by one, genomic approaches involve the systematic gathering and analysis of information about multiple genes and their evolution, functions, and complex interactions within networks of genes and proteins.

Genomics has two branches. One is *structural genomics*—studies of how genes and genomes are organized and how that varies among individuals, populations, and species. It includes characterization of the sequences of DNA nucleotides that encode proteins, as well as the DNA found between and within genes that does not code for proteins.

Using structural genomics, we can compare DNA sequences among individuals of a species to reveal minor variations in the DNA nucleotide code at certain positions in the genome, called "single-nucleotide polymorphisms, " or SNPs (pronounced "snips"). These SNPs can be responsible for genetic diseases, or for hypersensitivity or resistance to drugs or toxicants.

By comparing DNA sequences among species (called "comparative genomics"), scientists can identify changes in genomes that have occurred as species evolved. They can also begin to determine the function of specific DNA sequences shared among different species.

The second branch is *functional genomics*—the study of the RNA and proteins produced by genes (referred to as "gene expression"), and how these molecules interact to carry out cellular processes.

Among the most elegant and widely used tools of functional genomics is the microarray, or "gene chip" (see figure), which became available less than a decade ago. By using microarrays to simultaneously measure the amounts of hundreds or thousands of specific RNAs contained in cells or tissues, biologists can "see" what cells are doing and how they are responding to particular environmental conditions.

Genes reveal marine biodiversity

Though the genomics revolution immediately swept into biomedical research, its entrance into oceanography and marine biology lagged. But marine scientists at WHOI and elsewhere have now begun to take advantage of genomic methods and approaches, aided by three recent developments.

First, the costs of instruments to do genomic research, especially the costs of DNA sequencing, have declined dramatically over the past five years. Second, efforts to sequence genomes have started to include more marine species, from bacte-

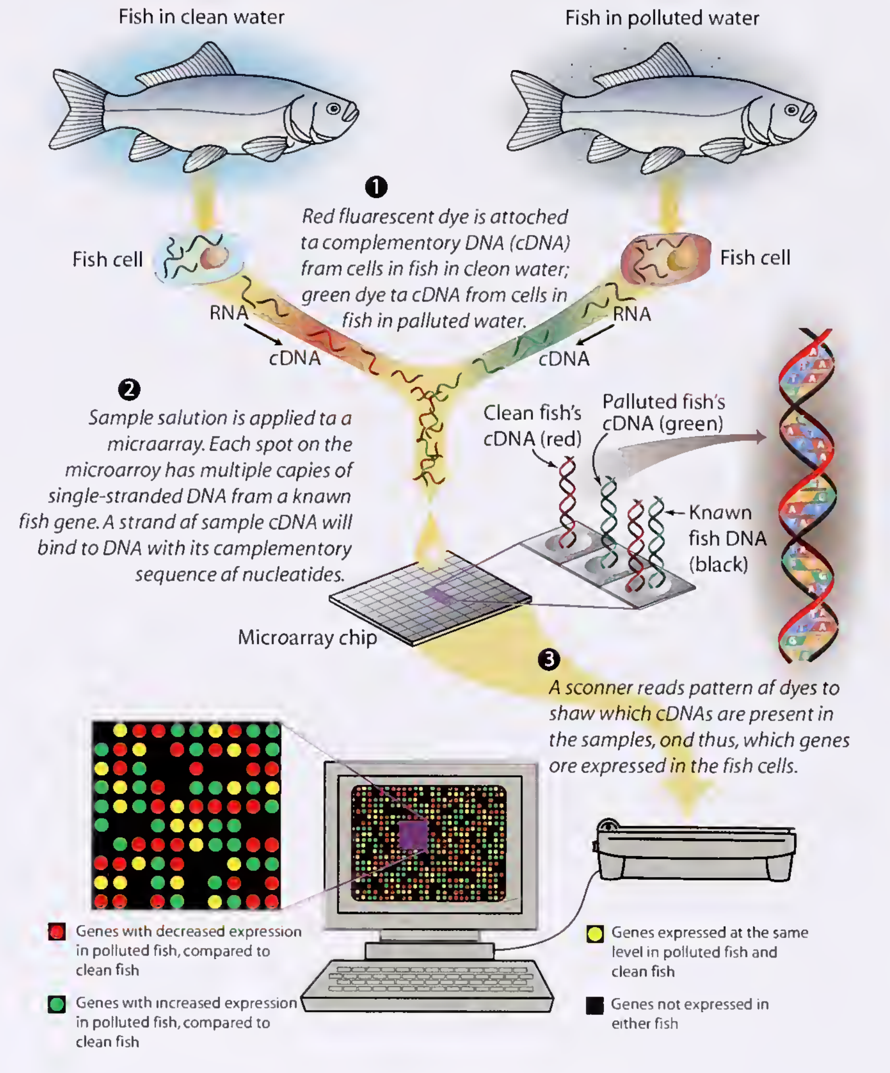
ria to animals. And third, recent studies have shown that genomic approaches can be used even if a species' genome sequence is not yet known. Marine organisms with unusual or unique adaptations, for example, can now be studied using genomics. In addition, by sequencing DNA from samples of seawater or ocean sediments, scientists can find new organisms by comparing the newfound genes with similar gene sequences of known organisms.

To study single-celled marine organisms, scientists are hampered because it is often difficult to replicate the microbes' undersea conditions in the laboratory and culture the microbes successfully. But molecular and genomic approaches are yielding important and sometimes surprising information about the diversity, abundance, and ecological roles of marine microbes in diverse environments, including extreme environments such as the deep sea and polar regions. (See "The Deeps of Time in the Depths of the Ocean," page 17.)

Recently, the genomes of several marine microbes have been sequenced, providing a window on their genetic, biochemical, and physiological adaptations to their diverse physical, chemical, and biological environments. Some of the microbes' unusual physiological abilities, inferred initially from genomic sequences taken from environmental samples, have been confirmed subsequently by detailed study of expressed proteins.

For example, Ed DeLong's research team at the Monterey Bay Aquarium Research Institute isolated genes encoding a novel type of light-harvesting pigment that mediates an unusual form of photosynthesis in marine bacteria. Genomic studies of uncultured bacterial samples from oceanic waters showed that these pigments are much more diverse and widespread than expected. These findings are changing the way we think about the importance of marine bacteria in the flow of carbon and energy in marine ecosystems, including their possible role in the uptake of atmospheric carbon dioxide.

How gene chips work



Jack Cook, WHOI Graphic Services

Genomic insights into evolution

Genomic information also provides a key to unlocking longstanding mysteries of evolutionary history. Scientists are comparing the characteristics of genomes—DNA sequences, gene structure, and chromosomal organization—to infer evolutionary relationships among organisms. Such studies are helping scientists construct the tree of life, which traces the evolution of organisms from ancestral single-celled beginnings to the diversity that exists today.

Such studies have shown that an organism's DNA can come not just from its direct ancestors but also from distantly related species. Though genes are transferred vertically (from parent to offspring), a surprising 17 percent of the DNA in some bacterial species has been acquired by horizontal gene transfer (between species). Genes encoding bacterial antibiotic resistance, a major problem in hospitals, are known to be passed around in this way, but the implications of horizontal gene transfer in the marine environment are not yet well understood.

To understand age-old evolutionary mysteries of how animals evolved such a variety of body plans—from jellyfish to mollusks, crustaceans, worms, and vertebrates—biologists are now using genom-

ics to elucidate the structure, expression, and evolutionary history of the genes responsible for generating morphological diversity during embryonic development. Genomic studies in a variety of animals, including tunicates (marine invertebrates that are close relatives of vertebrates), have helped reveal the importance of a set of genes known as the *Hox* cluster. The specific positions of the *Hox* genes on the chromosome influence how these genes are expressed during embryonic development and ultimately how they affect the shape of the embryo.

Genome sequencing in animals, plants, and fungi also has revealed that at certain times in evolutionary history, various lineages developed duplicate genomes—that is, extra sets of the same genes. The extra genes increase the chance that mutations providing advantageous anatomical, physiological or biochemical traits will be retained. In this way, genome duplications may promote biodiversity.

Genomic studies have shown that one or two whole genome duplications occurring more than 450 million years ago may have facilitated the evolution of vertebrates (animals with backbones). Another more recent genome duplication may have led to the extraordinary diversity of bony fishes (about 30,000 species), which account for about half of vertebrate species.

Genomic clues to symbiosis

Genomics is also providing insights into the factors that underlie symbiosis, the fascinating interrelationships between two organisms that can be either mutually beneficial (mutualism) or harmful to one member of the pair (parasitism). Genomic sequencing of symbiotic organisms has shown that dramatic changes in genome structure often occur during the evolution of their association. Parasites, for example, often exhibit reductions in genome size and gene number, accompanied by the loss of the ability to carry out certain biochemical reactions.

Scientists are also using microarray-based measures of gene expression to understand symbiotic mechanisms between reef-building corals and dinoflagellates that help corals grow and build their skeletons. The studies will also yield better understanding of coral bleaching, which occurs when the dinoflagellates leave or are ejected from the corals.

Adapting to the environment

Scientists have learned that changes in an organism's environment, including pollution, often elicit compensatory changes in the expression of specific genes. For example, Andrew Gracey and George Somero at Stanford University's Hopkins Marine Station have used microarrays to identify genes involved in the ability of a burrow-dwelling fish, the goby *Gillichthys mirabilis*, to adapt to the reduced oxygen levels (hypoxia) that occur in its intertidal burrows.

Similarly, scientists at WHOI are studying the genes and proteins involved in the response of fish to contaminants such as chlorinated dioxins and polychlorinated biphenyls (PCBs). At WHOI, Heather Handley-Goldstone and John Stegeman have used microarrays to identify genes associated with heart malformations caused by dioxin in embryonic zebrafish.

In my lab, we use genomic techniques to trace the evolution of genes encoding receptor proteins through which dioxins and PCBs cause altered gene expression and toxicity. We have found that fishes have more of these receptor genes than mammals, possibly explaining the extreme sensitivity of fish to these chemicals. At the same time, we are also studying how small changes in these genes—SNPs—might be involved in PCB resistance that sometimes develops in Atlantic killifish (*Fundulus heteroclitus*) living in highly contaminated sites such as the harbor in New Bedford, Mass.

From genomics to bioinformatics

Despite the progress in applying genomics to marine systems, challenges remain. One of the most significant is dealing with the huge amounts of data generated in genomic experiments, which must be analyzed in relation to environmental or physiological measurements collected at the same time. To accomplish this, we use *bioinformatics*—mathematical and computational methods for analyzing and visualizing genomic data.

As bioinformatic approaches become more sophisticated and essential, biologists without extensive mathematical backgrounds will need enhanced training in computational genomics and bioinformatics. We will also need to recruit more mathematicians and computer scientists into the marine science community.

The conceptual and technical advances associated with genomics are revolutionizing research in biology and medicine. The emergence of genomics gives the marine science community an unprecedented opportunity to address old questions in new ways and to formulate new questions stimulated by our expanding genomic understanding of life in the oceans.

Tom Kleindinst, WHOI

Mark Hahn first visited Woods Hole in 1966 when his father, who worked for Eastman Kodak in Rochester, N.Y., spent a week at the Marine Biological Laboratory on business. Left to his own devices, the eight-year-old boy wandered around the docks and spent hours at the National Marine Fisheries Service aquarium, fascinated with the fish, seals, and turtles on display. This nascent interest in marine biology remained quiescent while he pursued a B.S. in biological sciences at Harpur College of SUNY Binghamton and then a Ph.D. in biochemical toxicology at the University of Rochester School of Medicine and Dentistry. Given the opportunity to rekindle his marine interests through a Surdna Foundation postdoctoral fellowship at WHOI in 1987, he turned a one-year fellowship into a thriving research program in comparative and molecular toxicology that involves a large group of talented colleagues. Hahn lives on Martha's Vineyard with his wife, a kindergarten teacher, and son.

The Ocean Institutes

In 2000, Woods Hole Oceanographic Institution established four Ocean Institutes to accelerate advances in knowledge about the oceans and to convey discoveries expeditiously into the public realm. The Ocean Institutes' goals are to catalyze innovative thinking that can open up new scientific vistas, to spur collaboration among scientists in different disciplines, and to stimulate a rich and productive educational environment that will engage future leaders of oceanography. Concurrently, each Institute's mission is to shorten the time between acquiring knowledge and making it accessible to decision-makers who can use this information to benefit society.

The Deep Ocean Exploration Institute investigates Earth's dynamic processes beneath the oceans , where more than 80 percent of all earthquake and volcanic activity occurs and where the clues to understanding the inner workings of our planet lie. The seafloor is our window into the dynamic, fundamental processes that generate natural disasters, produce oil and mineral resources, create and destroy oceans and continents, build mountains and islands, and foster life.

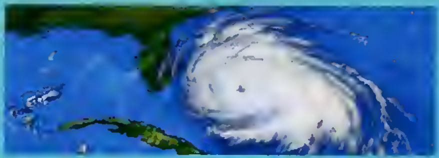
The Deep Ocean Exploration Institute:

- explores how our dynamic planet evolves and changes
- examines the basic forces that create earthquakes and volcanoes
- develops technology related to seafloor observatories and deep-submergence vehicles
- investigates unusual chemosynthetic communities of life on and below the seafloor
- explores potential new energy and mineral resources in the oceans

The Ocean Life Institute explores the ocean's extraordinary diversity of life—from microbes or whales—to identify ways to sustain healthy marine environments and to learn about the origin and evolution of life on Earth. The more we look into the oceans, the more we find remarkable life forms thriving in environments ranging from Antarctic sea ice to the volcanic crust below the seafloor.

The Ocean Life Institute:

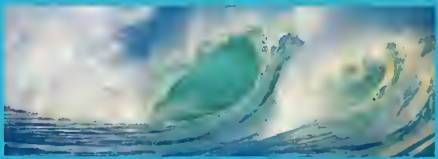
- explores biodiversity in the oceans
- finds ways to monitor and sustain the health of marine ecosystems
- studies marine life's physiological and ecological adaptations
- investigates the evolution of life in Earth's oceans
- develops new techniques and instruments to explore ocean life



The Ocean and Climate Change Institute seeks to understand the role of the ocean in regulating Earth's climate and to improve our ability to forecast future climate change. The ocean stores vast quantities of heat, water, and carbon dioxide and works with the atmosphere in regulating global and regional climates—on time scales ranging from days (storms and hurricanes), seasons (monsoons), years (El Niños), to centuries and longer.

The Ocean and Climate Change Institute:

- identifies the climatic effects of ocean circulation patterns
- develops an ocean-monitoring network to forecast climate changes
- examines geological records to better understand ocean behavior
- studies ocean dynamics that may trigger large, abrupt climate shifts
- evaluates the ocean's response to the buildup of greenhouse gases



The Coastal Ocean Institute examines one of the most vital—and vulnerable—regions on Earth: the coast. Our planet's exploding population has put stress on the fragile coastal ocean and has exposed more people to coastal hazards such as storms, beach erosion, and pollution. Understanding the complex, delicately balanced processes at work in coastal areas is the key to ensuring that they remain productive and attractive.

The Coastal Ocean Institute:

- studies basic processes underlying the coastal ocean's fertility
- provides sound science to guide coastal management policies
- examines uses of coastal resources, such as wind, oil, and fisheries
- identifies strategies to mitigate coastal hazards
- promotes awareness of the coastal zone's importance to society

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